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BEAUFORT ISLAND, REMNANT OF A QUATERNARY VOLCANO IN THE ROSS SEA, ANTARCTICA

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Summary

Beaufort Island, near the entrance to McMurdo Sound, is a remnant of a basaltic cone of about Last Interglacial age. More than three-quarters of it was quarried away by extensions of the Ross Ice Shelf or by glaciers during the Last Glaciation, leaving the remainder essential unmodified. Agglomerates, lavas, and tuffs of the cone rest unconformably on a pediment of horizontal tuffs and fine agglomerates, which show features that are either frozen-ground involutions or contortions caused by collapse of ice-tuff sandwiches. On the northern shore there is a cliffed bench at a height of about 25 ft. Its age and origin are uncertain but it could be a cliffed talus cone formed about 700 A.D., or a true marine bench formed about 5000 B.C. and since raised by post-glacial isostatic rebound of Antarctica.

INTRODUCTION

Beaufort Island, discovered and named by Sir James Clark Ross (1847, vol. 1, p. 217) lies near the entrance to McMurdo Sound about 12 miles north of Cape Bird on Ross Island, and 40 miles north of Mt Erebus (Fig. 1). The island blocks the rapid westward drift of pack ice and of giant tabular bergs calving from the adjacent terminal face of the Ross Ice Shelf, and consequently a close approach by sea is often difficult. There has been only one landing, by Seaman Paton of the *Morning*, who, against orders, walked walked across the sea ice to the south end of the island in 1903. Its topography is briefly described by Ferrar (1907, p. 7) and by Debenham (1923, p. 44), the latter account containing two sketches of it. The geology has not been

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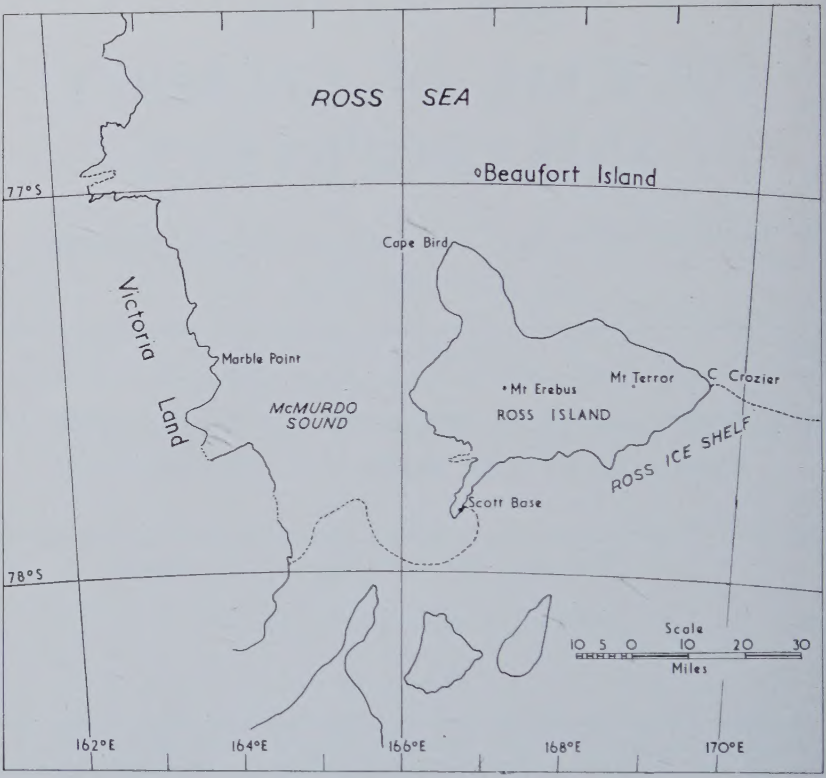

FIG. 1.—Locality map.

described, though the island is clearly volcanic like all the islands in the Ross Sea, and is shown as such in several geological maps.

On 12 December 1957, the ice-breaker U.S.S. *Glacier* on a passage from Kainan Bay to McMurdo Sound, approached the island from the east in calm sunny weather, and passed less than a mile from its northern shore. A landing was not practicable, but there was an excellent opportunity for observation of the geology through field glasses by Messrs B. L. Wood, I. C. McKellar, G. J. Lensen, and the writer, all geologists of the New Zealand Geological Survey Antarctic Expedition to Cape Hallett. A few days later a brief view of the island was obtained on a flight from McMurdo Sound to Cape Hallett.

TOPOGRAPHY

Ferrar (1907, p. 7) from distant views estimates that the island is about five miles long by two miles wide, and 1,000 ft high, whereas

Debenham (1923, p. 44) does not estimate its length and breadth, but states it is about 1,600 ft high. It is probably about two miles in radius and is about 1,600 ft high. Its appearance changes dramatically with change of viewpoint, and can be visualized if it is stated that the island is a remnant of a volcanic cone of which more than three-quarters has been removed by erosion, leaving the north-western "quarter" retaining nearly its original shape. The south, east, and north-east sides are steep cliffs (Fig. 2 and 3) rising to over 1,000 ft near the eastern corner of the island. The north-western side has the original slope of the cone of about 12° to 15° towards the sea, and is slightly concave; and it is partly covered by an ice cap at least 200 ft thick near the summit but much thinner on the flanks, and draining to a small ice-foot fringing part of the north-western shore of the island. On the southern part of the north-western slopes the ice cover is intermittent and there are large bare areas of red and black cinders and scree material.

VOLCANIC ROCKS

The lower 100 to 200 ft of the eastern and northern cliff-face of the island is nearly vertical and exposes vari-coloured grey, brown, and reddish tuff and agglomerate layers which taken as a whole are nearly horizontal, but in detail show many minor undulations and contortions (Figs 2 and 3). The ship was moving too quickly to allow time for full observation of the undulations, but though some of them might be a result of deposition of ash showers on an eroded land surface, others are so confused, contorted, and irregular in detail that they are probably frozen-ground phenomena called involutions (Flint, 1957, p. 200-1). Involutions are generally considered to result from freezing and thawing of water and ice within a porous bed, and in an Antarctic environment could be expected to occur in tuff and bedded agglomerate after deposition. Another similar mechanism that might explain the Beaufort Island features is collapse following the melting of thick irregular ice layers formed on the surface in the intervals between the eruptions of ash showers. Uncollapsed ice and tuff sandwiches of that kind are known on the flanks of Mt Erebus and elsewhere in the region.

The middle part of the cliff-face stands less steeply than the lower and upper parts, and appears to consist predominantly of poorly bedded fairly coarse agglomerate, dipping to the north-west at 12° or more, lying unconformably above the lower horizontal involuted tuffs. The agglomerate forms a wedge 400 to 500 ft thick near the eastern end of the island and probably less than 50 ft thick in the western end of the cliff-face. Conformably above the wedge of agglomerate at the base of the steep upper part of the cliff there is a prominent light-coloured band, about 150 ft thick, of vari-coloured tuff and agglomerate. Some of the light-coloured beds in this band are discontinuous, possibly mainly as a result of involutions or other frozen-ground and ice-sandwich features formed shortly after their deposition, and possibly

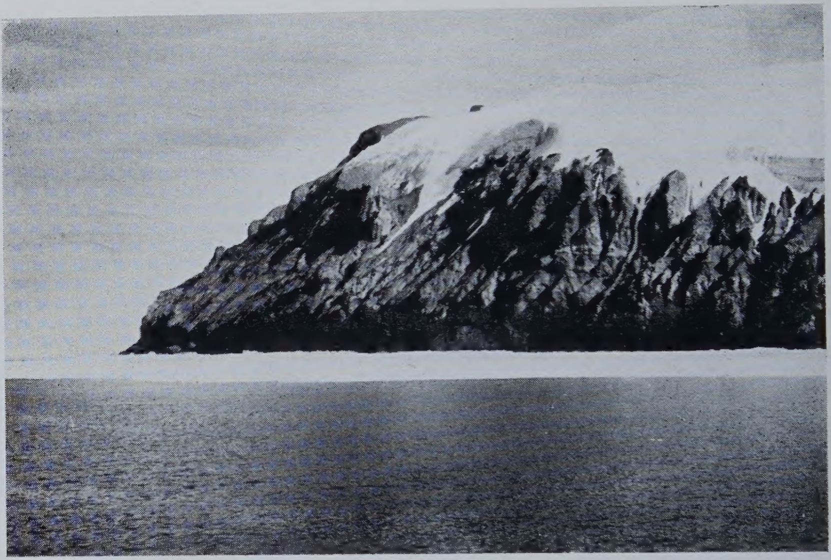

FIG. 2.—Eastern and north-eastern cliffs of Beaufort Island, with summit ice cap. *Photo*: *W. G. Croll.*

also because the tuffs were a slope-mantle produced by many small explosive eruptions. Above the tuff beds, and forming the upper steep cliffs, there is a sequence of about 300 ft of thin grey blocky lavas separated by darker layers that are probably in part scoriaceous upper and lower surfaces of the flows and in part ash and scoria beds. The flows dip north-west at 12° to 15° and descend nearly to sea-level at the western end of the cliff.

About 200 yards from the western end of the cliff there is a small prominent plug of dense blocky jointed light-grey basaltic rock which does not extend to the present surface, and a little further to the east a dark dyke about 6 ft wide is visible to a height of about 150 ft above sea-level and dips roughly west at 80°.

Petrographically, nearly all the rocks are probably basalts, but there may be also trachytic and phonolitic rocks like those of the adjoining McMurdo Sound district (Smith, 1954).

CONDITIONS OF ERUPTION AND AGE

The tuffs at the base of the cliffs might have been erupted from a vent several miles away, appear to be terrestrial, and seem to have been

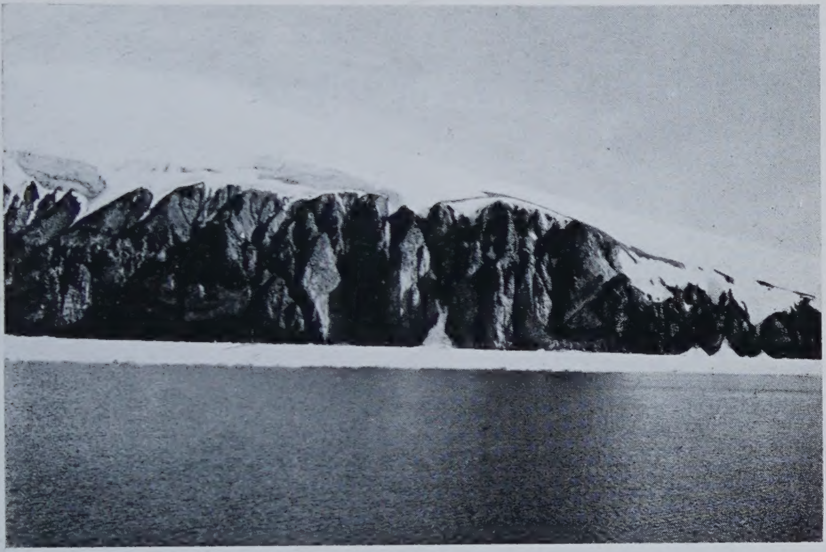

FIG. 3.—North-eastern cliff of Beaufort Island.
Photo: A. J. Heine.

thrown into involutions by frozen-ground or "ice-sandwich" processes that operate in regions where the mean annual temperature is below 0° C. On this surface a cone was built up to a height of about 2,000 ft above present sea-level by eruptions from a vent that clearly lay a short distance offshore from the present eastern end of the island, and the activity passed through three phases, dominant agglomerates being followed by tuffs and then by a sequence of lava flows.

The age of the volcano must be estimated on morphological evidence. That most of it has been removed by erosion suggests that it is no younger than the Last Glaciation (which occurred approximately 10,000 to 40,000 years ago), and that the remainder of it has been very little dissected suggests that it is no older than the Last Interglacial. In general terms the volcanism occurred in the Late Quaternary, and was part of the widespread volcanism in the Ross Sea region which probably commenced about the Pliocene and is still active at Mt. Erebus 40 miles to the south. (See Ferrar, 1907; David and Priestley, 1914.)

GLACIAL AND MARINE EROSION OF THE VOLCANO

There is no reason to suppose that the disappearance of more than three-quarters of the island, leaving the remainder practically unaltered. is a result of volcanic explosions or caldera collapse, but erosion by subaerial, marine or glacial agencies can be invoked.

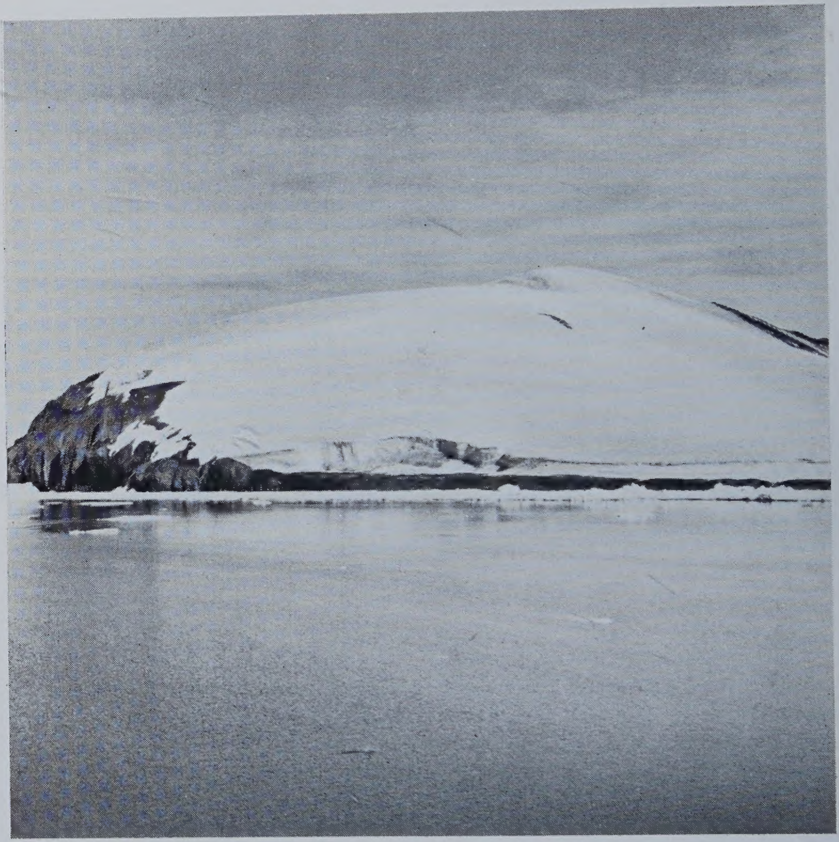

Fig. 4.—Beaufort Island from the north showing 25 ft bench.
Photo: *A. J. Heine.*

That the north-western slope of the island has nearly its original shape (Figs 4 and 5) shows that subaerial weathering, stream erosion, and solifluction have been unimportant. Normal marine erosion by waves is effective for only about three months in the year but might have been more effective during warmer periods between the Last Glaciation and the present day. Nevertheless, the time available for normal marine erosion seems too short to allow removal of most of the volcano and the formation of a 1,000 ft cliff, though it has clearly caused steepening of the lower part of the cliff. It is significant perhaps that the island is cliffed on the sides that are most exposed to a sea-current moving westward at a speed of several knots and carrying icebergs and broken sea-ice. The erosive effect of floating ice-blocks depends on the extent to which they are thrown against the island by

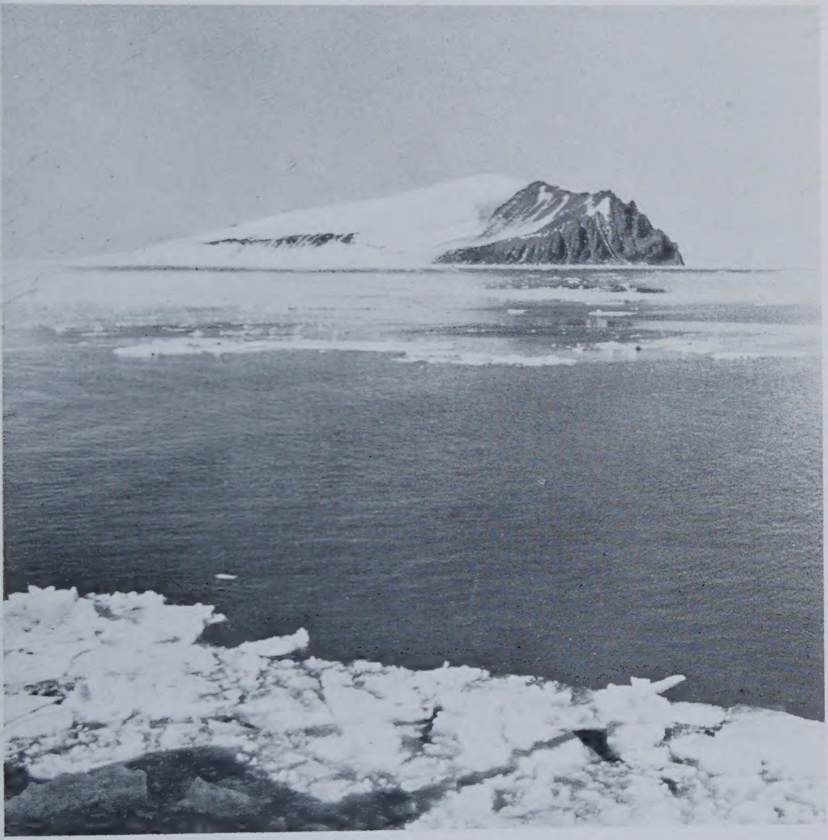

FIG. 5.—Beaufort Island from the west. *Photo: A. J. Heine.*

currents, and by waves, but on intuitive grounds, and from scanty observations on the shore near Cape Hallett, it seem unlikely that they are as effective as waves. A more likely explanation of the cliffing of the island is that it is a result of erosion by either normal glaciers or by an extension of the Ross Ice Shelf during one or more Quaternary ice advances. That glaciers in the Ross Sea region were formerly more extensive is well known, and it has been suggested that a former Ross Ice Shelf might have extended northwards, even to Scott Island, from glacier termini in the vicinity of the Pennell and Iselin Banks (see Harrington and McKellar, 1958). Beaufort Island, and indeed other islands and coasts in the Ross Sea, could scarcely have escaped considerable erosion during phases of growth and retreat of the Late Quaternary glaciers and ice shelves which must have flowed around them. Priestley and David (1910, p. 790) have in fact briefly stated that Beaufort Island "shows distinct evidence of having been overriden by ice", but it seems unlikely that the island was ever completely submerged beneath moving ice because the north-western slopes have not been extensively modified.

CLIFFED COASTAL BENCH

Along the north shore of the island for about half a mile there is a cliffed bench-like feature that is about 25 ft high and about 20 yards wide at its eastern end where it is built out from a low rock face (Fig. 4). The ice-cap covering part of the island descends to the rock face, and breaks on top of it, so that most of the bench is obscured by ice-talus. The bench seems to consist of coarse angular talus rather than beach-rounded gravels, and was carefully examined through field-glasses, but its origin and age are doubtful.

It could be a talus apron that has been cliffed so that the remnant of its surface is deceptively like a true marine bench. If that is so it could have formed only by the supply of talus from above, before the growth of the ice-cap, possibly in the warm period centred around 700 A.D. It could also be a talus-deposit that accumulated in a moat formed by radiation of heat from sun-warmed rock at the contact of the rock face and a former piedmont glacier. It might be, however, a true marine bench, and if so, it has almost certainly formed since the Last Glaciation, because an older bench would have been removed from such an exposed position. Attempts at correlation with Late Quaternary deposits and benches described elsewhere in the McMurdo Sound region (David and Priestley, 1914) are not helpful, because some of these features are deposits apparently raised from the sea-floor by glacier-ploughing, and others were examined before the development of the glacio-eustatic theory that stimulates present-day work on coastal benches. Post-glacial benches in other regions are apparently less than 10 ft high (Zeuner, 1950; Godwin, 1956) but it is possible that the Beaufort Island bench formed as a shore-line feature during the Climatic Optimum about 5000 B.C., and has since been raised to its present height, perhaps by isostatic rebound of Antarctica since the Last Glaciation.

A radiocarbon age, that would be a useful check on these hypotheses, may yet be obtained if it is found that the bench was colonized by penguins during the warm period about 700 A.D., or during the Climatic Optimum.

REFERENCES

DAVID, T. W. E.; PRIESTLEY, R. E., 1914: Glaciology, Physiography Stratigraphy, and Tectonic Geology of South Victoria Land. *Rep. Sci. Inves. Brit. Antarctic Exped. 1907-9, Geology 1.* William Heinemann, London.

DEBENHAM, F., 1923: Report on the Maps and Surveys. *Brit. (Terra Nova) Antarctic Exped. 1910-1913 Rep.* Harrison and Sons, London.

FERRAR, H. T., 1907: Report on the Field-Geology of the Region Explored during the "Discovery" Antarctic Expedition, 1901-4. *National Antarctic Exped. 1901-1904, Nat. Hist. Vol. 1, Geology* : 1-100. British Museum (Nat. Hist.), London.

FLINT, R. F., 1957: "Glacial and Pleistocene Geology". John Wiley and Sons, New York. 553 pp.

GODWIN, H., 1956: "The History of the British Flora". C.U.P. 384 pp.

HARRINGTON, H. J.; MCKELLAR, I. C., 1958: A Radiocarbon Date for Penguin Colonization of Cape Hallett, Antarctica. *N Z. J. Geol. Geophys. 1 (3)* : 571-6.

PRIESTLEY, R. E.; DAVID, T. W. E., 1910: Geological Notes on the British Antarctic Expedition, 1907-1909. *Compte Rendu du XI:e Congres Geologique International* : 767-811.

ROSS, J. C., 1847: "Voyage of Discovery and Research in the Southern and Antarctic Regions during the years 1839-43". Vol. 1. John Murray, London

SMITH, W. CAMPBELL, 1954: The Volcanic Rocks of the Ross Archipelago. *Brit. Antarctic ("Terra Nova") Exped., 1910; Nat. Hist. Rep.; Geol. II (1)* : 1-107. British Museum (Nat. Hist.), London.

ZEUNER, F. E., 1950: "Dating the Past". Methuen, London. 474 pp.

THE AGE OF THE TAKITIMU GROUP OF WESTERN SOUTHLAND

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Summary

A marine fauna low in the Takitimu Group is discussed and considered to be probably Sakmarian (Lower Permian) from its affinities to the faunas from the lower Dalwood Group of the Hunter Valley in New South Wales, and correlative beds of Queensland. A pleurotomarid near the base of the group is close to or identical with a Queensland species from beds correlated with the Lochinvar or Allandale Formation of the Hunter Valley. Probably the Takitimu Group is Sakmarian and lower Artinskian.

Introduction

The Takitimu Group of Southland lies above the Longwood Complex and below the Permian Productus Creek Group, and comprises in the type area about 60,000 ft of pyroclastic breccias, spilitic and andesitic tuffs, pillow lavas, andesite flows and sills, and red and green mudstone and sandstone. In recent publications, geologists have tentatively referred the group to the Carboniferous, examples including Wellman (1956), Mutch (1957), and Fleming (1957), and the recently published Geological Map of New Zealand (1958). The reason given for a Carboniferous age by Mutch (1957, p. 502) is that the group underlies the Productus Creek Group, from which a Lower Permian fauna has been described by Fletcher, Hill, and Willett (1952). Mutch (1957, p. 504) stated that the two groups are separated by a non-sequence which, as the lower Productus Creek beds are probably no older than upper Artinskian (from unpublished faunal studies by the writer), represents at least lower Artinskian and Sakmarian time.

Nevertheless, even the few fossils recorded by Mutch (1957, p. 501) from the Takitimu Group seem incompatible with a Carboniferous age. These fossils, most of them low in the sequence from bluffs at Wairaki Gorge, have been listed as *Euryphyllum, Chonetes, Strophalosia, Spirifer, Maitaia* (now *Atomodesma*), and *Deltopecten*. The Zaphrentoid coral *Euryphyllum*, identified by Miss H. Leed, is unknown below the Permian, and *Strophalosia* and *Deltopecten* are restricted to the Permian in the closely allied faunas of Australia. Although *Spirifer* is rare in the Permian, the Takitimu specimens in fact belong to the common Permian genus *Neospirifer*. The Takitimu specimens referred to the long-ranging upper Paleozoic genus *Chonetes* are internal chonetid casts that cannot be placed in a genus with accuracy. ("*Nuculana*" was also included in the list by Mutch, but this record should be deleted, as neither this genus nor the Paleozoic Nuculanid genera such as *Polidevcia, Phestia,* or *Culunana* are known from the group).

From additional fossil collections made by Mutch and kept at the N.Z. Geological Survey, the Takitimu beds may be correlated approximately with the Lower Permian Dalwood Group of the Hunter Valley in New South Wales. Only the faunas from the two lowest fossil localities in the Takitimu Group will be discussed, and, as these are apparently Sakmarian, a Lower Permian age is indicated for the group.

FAUNA FROM WAIRAKI GORGE, NZGS 5885

Fossils from Wairaki Gorge include:

Cancrinella aff. *farleyensis* (Etheridge and Dun)
Terrakea n.sp. aff. *pollex* Hill
Strophalosia ?preovalis Maxwell n.var.
Plekonella n.sp.
Psilocamara n.sp.
Neospirifer ?hardmani (Foord)
Gen.nov. allied to *Notospirifer* Harrington 1955, n.spp.
Cancellospirifer n.sp.
Atomodesma n.sp.
Deltopecten limaeformis (Morris)
Streblochondria sp.
Peruvispira n.sp.
Keeneia, n.sp.
Euryphyllum sp.

Of these, the following genera are restricted to the Permian: *Terrakea, Plekonella,** Notospiriferid gen.nov., *Cancellospirifer, Atomodesma, Keeneia,* and *Euryphyllum,* and in Australia *Strophalosia* and *Deltopecten* are unknown below the Permian. Species of *Peruvispira* have also been described only from the Permian, but this genus also occurs in the Carboniferous of New South Wales (Dr K. S. W. Campbell, pers.comm.). The other genera are abundant in the Permian, and there is not one species or genus from Wairaki Gorge that is restricted elsewhere to pre-Permian faunas.

Affinities with Faunas from New South Wales

Within the Dalwood Group or "Lower Marine Series" of the Hunter Valley in New South Wales, four formations are recognized, the Farley, Rutherford, Allandale, and Lochinvar at the base (Hanlon and Booker

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*The New Zealand species of *Plekonella* has crenulate dental sockets, whereas no mention is made of crenulations in the type species *Plekonella acuta* (Campbell 1953. Subsequently, Dr K. S. W. Campbell has found crenulate sockets in the type species (letter, 22 July 1958).

in Hill, 1955, fig. 5). Generally, the Farley beds are referred to the lower Artinskian, as they have yielded an Artinskian ammonoid (Teichert, 1953), and underlie the Greta Coal Measures and the Branxton sub-group, from which another Artinskian ammonoid has been described by Teichert and Fletcher (1943). Although there are no ammonoids to date the underlying Rutherford, Allandale, and Lochinvar formations with such accuracy, these three formations are generally referred to the Sakmarian by Australian geologists (David and Browne, 1950), as their faunas resemble the overlying Farley fauna to some extent, suggesting that perhaps little time elapsed between the deposition of each formation. Moreover, the faunas differ considerably from the Lower Carboniferous faunas of eastern Australia, and as a whole are close to the Artinskian and Kungurian faunas of the Maitland Group or "Upper Marine Series". Further evidence for a Permian age is adduced by Walkom (1944) on the presence of the *Glossopteris* flora, although elements of such a flora are apparently represented in the Upper Carboniferous (Stephanian) of South America (Hill, 1955, p. 104; Caster *in* Mayr *et al.*, 1950, pp. 125–6). Unfortunately, there are few macro-fossils in common with the well-dated Lower Permian deposits of Western Australia (Teichert, 1951; Dickins, 1957), so the Sakmarian age is not proven.

Amongst the Dalwood forms, *Cancrinella farleyensis* is chiefly characteristic of the Farley beds, but is also listed by Osborne (1949) from the Lochinvar Formation, so that the species apparently ranges throughout the group. Plicate and smooth species of the new Notospiriferid genus are represented in the Takitimu fauna, and allied or identical species are particularly abundant in eastern Australia.

Of the Mollusca, *Deltopecten limaeformis* (Morris) ranges throughout the Dalwood and into the Maitland Group, or the "Upper Marine Series". A more diagnostic fossil is the new species of *Keeneia*, a characteristic form with well-defined spiral lirae, apparently identical with an unnamed new species figured by Dickins (1957, pl. 9, figs 6–8) from the Allandale Formation. According to Mr J. M. Dickins, of the Bureau of Mineral Resources, Geology, and Geophysics, Canberra (pers. comm.), this species in New South Wales is apparently restricted to the Allandale, suggesting that the beds at Wairaki Gorge may be correlated with this formation.

Affinities with Queensland Faunas

In the Springsure Shelf of the Bowen Basin in Central Queensland, the lower part of the generalized upper Paleozoic succession given by Webb (1956) is as follows:

Ingelara Shale
Aldebaran Sandstone
Cattle Creek Shale

Undivided Fresh-water Sediments
Lower Shales and Mudstones
Basal Conglomerate
Andesite

Judging from unpublished work by the writer, the Aldebaran Sandstone is probably equivalent to part of the upper Takitimu Group, and the fauna of the Ingelara Shale is close to that of the lower Productus Creek beds. The Cattle Creek Shale has a rich Lower Permian fauna which differs from the fauna of the Ingelara Shale, and is related to that of the Takitimu Group at Wairaki Gorge, having *Cancrinella farleyensis* and *Strophalosia preovalis*. Other Springsure faunas that show resemblances to the collections from Wairaki Gorge come from the Cracow and Dilly beds. The Cracow fauna includes *C. farleyensis* and *Terrakea pollex*, and *T. pollex* occurs in the Dilly beds. Hill (1950) considered that the Cracow and Dilly faunas are probably Sakmarian.

Formerly the Cattle Creek Shales were correlated with the Dilly and Cracow beds (Hill, 1950), but subsequently oil borings in the Springsure anticline have shown that the Cattle Creek Shale has an upper and a low member, each possibly with a different fauna, and it is uncertain which member is equivalent to the Dilly and Cracow beds. Webb (1956, p. 2331) considers that only the lower shales correspond with the Dilly Shale, but more faunal confirmation is required. As, in addition, differences between the upper and lower faunas of the Cattle Creek Shale are yet to be described, there can only be a general correlation of the Wairaki Gorge fauna with faunas of the Springsure Shelf.

In the Yarrol Basin, Maxwell (1954) correlates a limestone and underlying faunas with the Cattle Creek fauna (in the broad sense). Several Yarrol species are close to forms from Wairaki Gorge, the fauna including *Terrakea pollex* Hill, and a new variety of *Strophalosia preovalis* that shows some rememblances to the new variety from Wairaki Gorge. The Takitimu species of *Cancellospirifer* is possibly identical with *Cancellospirifer* sp. figured by Maxwell (1954, pl. 3, figs 24–27) from 3,000 ft below the limestone. A Sakmarian age was assigned to these faunas by Maxwell, and an upper Dalwood correlation suggested.

Affinities with Faunas from Western Australia

Neospirifer from Wairaki Gorge is close to *Neospirifer hardmani* (Foord), which is characteristic of the lower Artinskian Callytharra Formation and the Sakmarian Lyons Group of the Carnarvon Basin in Western Australia.

Further Evidence for a Sakmarian Age

The few resemblances to species beyond Australia suggest a Sakmarian age. Externally, *Streblochondria* sp. from the Takitimu Group is close to *S. eichwaldti* (Stuckenburg), and the new species of *Peruvispira* is close to *P. delicata* Chronic from the Sakmarian Copacabana Group of Peru.

The new species of the smooth Stenoscismatid genus *Psilocamara* Cooper (=*Laevicamera* Grabau) externally resembles *P. donica* (Rotai), originally described from the Visean Beschevo Limestone of the Donetz basin, and also reported by Merla (1934) from the Sakmarian Schwagerina Limestone of Rimu in the Karakorum Range. Internal details of *P. donica* are little known.

FAUNA FROM NZGS 6054

Approximately 2,000 ft below the beds at Wairaki Gorge, and about 1,000 ft above the base of the Takitimu beds, is the lowest fossiliferous locality of the group. Two species are present, a single external cast of a Dielasmid, and numerous specimens of a pleurotomarid close to *Mourlonia*. The gastropod is very similar to and possibly identical with a specimen described by Maxwell (1954) from sandstones occurring below the limestone in the Yarrol Basin. Maxwell noted that the Yarrol species resembles *Mourlonia helicinaeformis* (Koninck 1877) from Carboniferous limestone at Burragood in New South Wales, but this species lacks the radial and weak spiral ornament of the Queensland and New Zealand specimens. The sandstones are correlated by *Eurydesma* with the Lochinvar or Allandale Formation of the Hunter Valley. To be consistent with the Allandale correlation suggested by the *Keeneia* from Wairaki Gorge, it could be proposed that the sandstone fauna is Lochinvar, and the limestone fauna Allandale, but it may be hazardous to attach too much importance to correlations based on gastropods.

CONCLUSION

The Takitimu faunas are to be correlated in a general way with those of the Dalwood Group in New South Wales and the Cattle Creek Shale in Queensland. Hence the group is probably Lower Permian rather than Carboniferous. On present evidence, the faunas low in the sequence at NZGS 5885 and 6054 are more likely to be Sakmarian than Artinksian. Thus they are probably older than the Farley Formation at the top of the Dalwood Group, but it will be difficult to establish definite correlations until the faunas from the Dalwood formation and coeval beds of Queensland are further described.

There is such a great thickness of Takitimu beds that the upper part of the group is probably lower Artinskian, equivalent to the Farley Formation. If this suggestion is true, the Takitimu Group ranges from Sakmarian to lower Artinskian, and the non-sequence between the Takitimu and Productus Creek groups must be infra-Artinskian, and of comparatively short duration.

ACKOWLEDGEMENTS

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REFERENCES

CAMPBELL, K. S. W., 1953: The Fauna of the Permo-Carboniferous Ingelara Beds of Queensland. *Dep. Geol. Univ. Qd. Pap. 4 (3).*

DAVID, T. W. E.; BROWNE, W. R., 1950: "The Geology of the Commonwealth of Australia." Edward Arnold, London.

DICKINS, J. M., 1957: Lower Permian Pelecypods and Gastropods from the Carnarvon Basin, Western Australia. *Bur. Min. Resour. Aust. Bull. 41.*

FLEMING, C. A., 1957: Trans-Tasman Relationships in Natural History, *in* "Science in New Zealand." A. J. Reed, Wellington; pp. 228–46.

FLETCHER, H. O.; HILL, D.; WILLETT, R. W., 1952: Permian Fossils from Southland. *N.Z. geol. Surv. Pal. Bull. 19.*

HARRINGTON, H. J., 1955: The Permian *Eurydesma* Fauna of Eastern Argentina. *J. Paleont. 29*: 112–28.

HILL, D., 1950: The Productinae of the Artinskian Cracow Fauna of Queensland. *Dep. Geol. Univ. Qd. Pap. 3 (2)*: 1–36.

———, 1955: Contributions to the Correlation and Fauna of the Permian in Australia and New Zealand. *J. geol. Soc. Aust. 2*: 83–107.

KONINCK, L. G. DE, 1877: Recherches sur les Fossiles paléozoiques de la Nouvelle-Galles de Sud (Australie). *Mem. Soc. Sci. nat. Liége Mém. ser. 2, 6, 7.*

MAXWELL, W. G. H., 1954: The Upper Paleozoic Formations of the Yarrol District, Queensland. Thesis for Diploma of Imperial College, Lond. (unpublished), lodged in the Department of Geology, Imperial College, London.

MAYR, E., *et al.*, 1950: The Problem of Land Connections Across the South Atlantic, with Special Reference to the Mesozoic. *Amer. Mus. nat. Hist. Bull. 99 (3).*

MERLA, G., 1934: Fossili anthracolitici del Caracorum. *Spedizione italiana de Fillippi nell' Himalaia Caracorum e Turchestan Cinese (1913–14) ser. 2, 5*: 101–319.

MUTCH, A. R., 1957: Facies and Thickness of the Upper Paleozoic and Triassic Sediments of Southland. *Trans. roy. Soc. N.Z. 84*: 499–511.

OSBORNE, G. D., 1949: The Stratigraphy of the Lower Marine Series of the Permian System in the Hunter River Valley, New South Wales. *Proc. Linn. Soc. N.S.W. 74*: 203–23.

ROTAI, A., 1931: Brachiopods and Stratigraphy of the Lower Carboniferous of the Donetz Basin. *Trans. geol. prosp. Serv. U.S.S.R. 73*: 35–144.

TEICHERT, C., 1951: The Marine Permian Faunas of Western Australia. *Paläont. Z. 24*: 76–90.

———, 1953: A New Ammonoid from the Eastern Australian Permian Province. *J. roy. Soc. W. Aust. 87*: 46–50.

TEICHERT, C.; FLETCHER, H. O., 1943: A Permian Ammonoid from New South Wales and the Correlation of the Upper Marine Series. *Rec. Aust. Mus. 21*: 156–63.

WALKOM, A. B., 1944: The Succession of Carboniferous and Permian Floras in Australia. *J. roy. Soc. N.S.W.* [President. Addr.] *78*: 4–13.

WEBB, E. A., 1956: Review of Exploratory Oil Wells Penetrating Permian Sections in Central Queensland, Australia. *Bull. Amer. Ass. Petrol. Geol. 40* : 2329-53.

WELLMAN, H. W., 1956: Structural Outline of New Zealand. *N.Z. Dep. sci.industr. Res. Bull. 121.*

N.Z. GEOLOGICAL SURVEY, 1958: "Geological Map of New Zealand." N.Z. Department of Scientific and Industrial Research, Wellington.

ILMENITE DEPOSITS IN NEW ZEALAND

By D. S. NICHOLSON, J. J. S. CORNES, Dominion Laboratory, and W. R. B. MARTIN, Victoria University of Wellington

(Received for publication, 16 June 1958)

Summary

A reconnaissance survey in 1948 shows that on the South Island West Coast beaches between Karamea and Jacksons Bay there is available upwards of 1,000 million tons of dredgable sand from which ilmenite and small amounts of radioactive minerals and gold could be recovered.

The most important locality is immeditely south of the Buller River, near Westport, where two large beach deposits are estimated to contain over 90 million tons of sand. Nineteen posthole bores, ranging in depth from 4 to 20 ft, averaged 5·5% of ilmenite, assaying 44% to 45% TiO_2.

INTRODUCTION

Though knowledge of ilmenite deposits in New Zealand (Fig. 1) is still very incomplete as regards quantities and average TiO_2 content, the fundamental difference between the ironsands of the North and South Islands (West Coast) has long been known. Cox (1881) of the New Zealand Geological Survey pointed out that in the latter the magnetite and the ilmenite occur as individual grains, whereas, as shown by Skey (1898), the titanium in most North Island sands occurs mainly in titanomagnetite.

Magnetic concentration of Taranaki ironsands (Hutton, 1945) yields a major, strongly magnetic fraction of *titanomagnetite* containing 49·99% Fe_2O_3, 29·46% FeO, 8·57% TiO_2, 0·39% V_2O_3, and a minor, less strongly magnetic fraction of *titanhaematite* containing 83·1% Fe_2O_3, 5·8% FeO, 9·6% TiO_2. On the other hand, magnetic concentration of South Island sands gives a strongly magnetic fraction of *magnetite* containing no TiO_2, and a larger, weakly magnetic fraction of *ilmenite* containing 44% to 45% TiO_2.

This paper is based on a reconnaisance survey in 1948 by D. S. Nicholson and W. R. B. Martin, and sand separations and chemical analyses by J. J. S. Cornes. The location and quantity data from this reconnaissance survey are the best available to date, but chemical work in progress by one of the authors (W.R.B.M.) will modify and amplify the preliminary chemical analyses reported here. This paper summarises the knowledge available in 1949 of ironsands of the South Island, with particular reference to their value as a source of ilmenite. Ilmenite deposits in the North Island have since been investigated by Nicholson and Fyfe (1958).

In January 1947, the Dominion Laboratory (unpublished data) in reporting to the Geological Survey on samples collected for Dr

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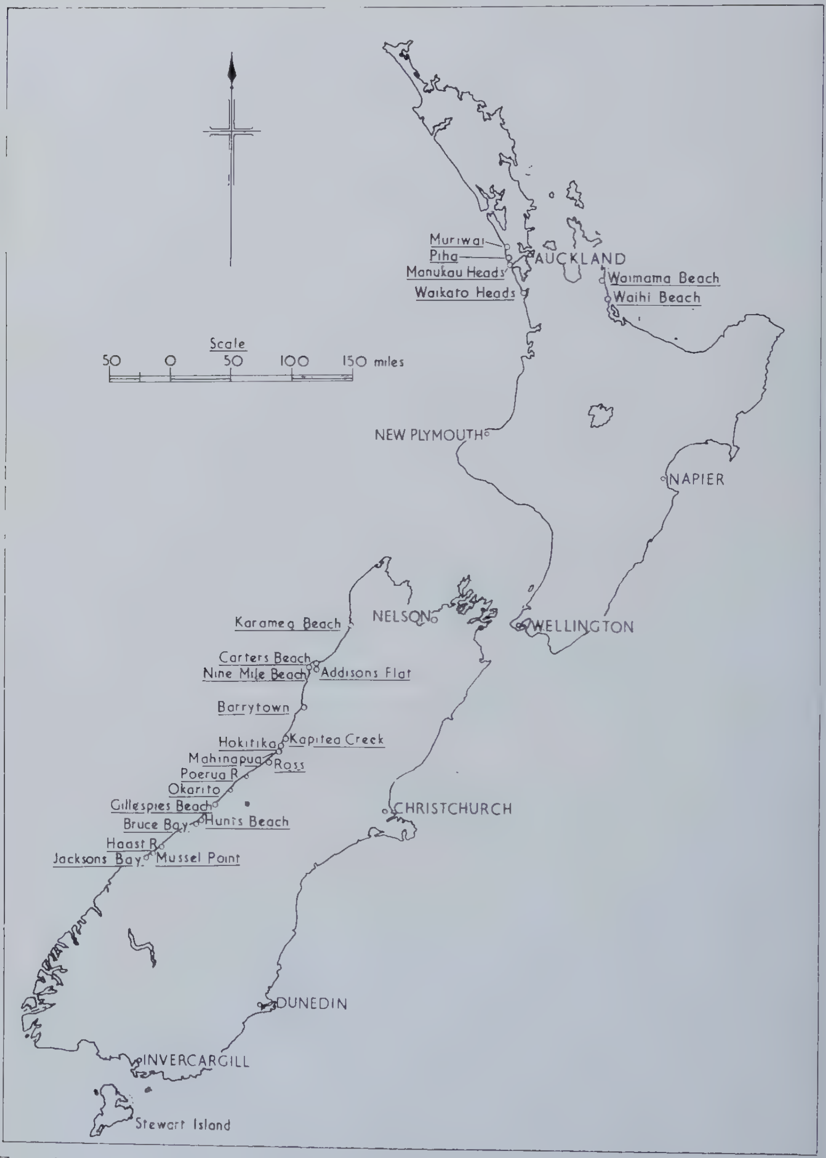

FIG. 1.—Sketch map of New Zealand showing localities of ilmenite deposits (underlined).

Gillson of Messrs Du Pont de Nemours Ltd., commented on a sample of black sand from Waimama Beach on the eastern side of Cape Colville Peninsula. Of this sample 76·5% was ilmenite, containing 44% TiO_2. It was commented that there was "probably no great quantity of Cape Colville blacksands".

A reconnaissance survey by H. E. Fyfe, D. Kear, and D. S. Nicholson (unpublished data) in 1957 showed that ilmenite occurs also on Waihi Beach. Nine posthole bores, average depth 13 ft contained an average of 5·9% of ilmenite. Analyses of three magnetically separated samples of ilmenite gave 40·0%, 34·4%, 27·2% TiO_2.

SOUTH ISLAND DEPOSITS

In a rapid survey, carried out by two of the authors (D.S.N. and W.R.B.M.) primarily to determine the South Island resources of magnetite, all the main deposits between Karamea and Bruce Bay were surface sampled. The main beaches between Bruce Bay and Jackson's Bay were later sampled, so that an assessment of the potentialities of the main beaches of the West Coast as sources of ilmenite is now available.

Results are given in the tables:
Table 1 shows the percentages of ilmenite and magnetite in each

TABLE 1.—Percentages of Ilmenite and Magnetite

Locality	Grade of Sample	Ilmenite (%)	Magnetite (%)
Jacksons Bay Aerodrome	Small surface concentration	3·5	33·8
Midway between Mussel Pt. and Waiatoto R.	Average of surface 2 ft	0·1	1·8
Mussel Point	Average of surface 2 ft	0·6	0·2
Beach 2 mls S. of Haast River	Average of surface 2 ft	0·1	0·1
Beach 1 ml. N. of Haast River	Surface concentration	21·6	10·5
Bruce Bay	Surface concentration	16	N.A.
Bruce Bay	Average surface sand	9	N.A.
Hunts Beach	Surface concentration	15·5	N.A.
Gillespies Beach	Surface concentration	20	20·8
Gillespies Beach	Average surface sand	10	N.A.
Okarito 5 mile Beach	Surface concentration	28·6	1·1
Okarito Beach	Surface concentration	25	N.A.
Okarito 3 mile Beach	Surface concentration	43·7	5·0
Mouth of Poerua River	Surface concentration	24	N.A.
Ross Beach	Average surface sand	6·2	0·03
Mahinapua, near lake	Surface concentration	14	N.A.
Hokitika 1 ml. S. of river	Average surface sand	8	N.A.
Kapitea Ck., N. of Hokitika	Average surface sand	8·6	1·0
Barrytown	Dredge concentrate	28·4	N.A.
Addisons Flat, S. of Westport	Surface sand	5·6	0.·1
Nine Mile Beach, S. of Cape Foulwind	Surface concentration	25·5	0·9
Carters Beach, Westport	Surface concentration	14·6	0·4
7 mls. S. Karamea River	Average surface sand	8	N.A.
5 mls. S. Karamea River	Surface concentration	27	N.A.

N.A.—Not available.

sample, as determined by separation of the magnetite by hand magnet, followed by electro-magnetic separation of the more feebly magnetic ilmenite from the garnet and non-magnetic minerals, using a magnetic refraction separator (Officer, 1947), and the Frantz Isodynamic Magnetic Separator.

Table 2 gives chemical analyses of ilmenites from the more significant deposits, together with analyses of ilmenites from overseas sources for comparison.

TABLE 2—Chemical Analyses of Ilmenite Samples.

Locality	Fe (%)	TiO_2 (%)	V_2O_5 (%)	NnO (%)	Cr_2O_3 (%)
SOUTH ISLAND ILMENITES			Less than		Less than
Gillespies Beach	32·5	44·5	0·05	2·5	0·01
Okarito Beach	32·2	44·5	0·05	2·5	0·01
Nine Mile Beach, S. of Cape Foulwind	32·5	45	0·05	2·5	0·01
Karamea, 7 mls. S. of Karamea River	32·5	44·5	0·05	2·5	0·01
Pure ilmenite FeO. TiO_2 (theoretical)	36·8 (47·3% FeO)	52·7			
Pure 'arizonite' Fe_2O_3. $3TiO_2$	28·0	60·0			
Patea (Taranaki) Titanomagnetite	53-59	7·0-9·0	0·3-0·4	0·7	Nil
FOREIGN ILMENITES (Gillson, 1949)					
Travancore (India) "M.K." (Arizonite-Ilmenite Mixture)	30·6	54·1	0·23		0·09
Travancore "Quilon" (Arizonite-Ilmenite mixture)	24·7	60·4	0·36		0·17
Arkansas	32·1	47·7	0·24		0·53
Norwegian (rock)	35·3	44·0	0·30		0·01
Malay States (tin placer residues)	31·1	53·4	0·04		0·01
Cudgen, New South Wales	32·2	51·2	0·21		2·50
Jacksonville, Florida	22·7	60·3	N.D.		N.D.
Trail Ridge, Florida		64·0			

Table 3 gives estimates of the order of quantities of sand available in the various localities. In making these estimates, it has been assumed that the logical large-scale method of working these deposits would be by some form of dredging, either standard bucket-dredging as for gold or tin or the more mobile dragline-dredging. The length of the beach areas as given is approximately correct, but the figures given

TABLE 3.—Quantities of Sand.

Locality	Length of Deposit (yards)	Average Width of Deposit (yards)	Average Depth of Deposit (feet)	Volume cu yd. × 10^6	Tonange × 10^6 @ 1·5 tons per cu. yd.
Haast R. to Tauperikaka Point	14,000	300	30	42	63
Bruce Bay	7,000	200	30	14	21
Hunts Beach	7,000	400	30	28	42
Gillespies Beach	5,000	300	40	20	30
Okarito Five Mile Beach	4,800	300	30	14·4	21·6
Okarito Three Mile Beach	2,500	300	30	7·5	11·25
Okarito to Waitaki Bluff	12,000	200	30	24	36
Abut Hd. to Poerua River	15,000	200	30	30	45
Bold Hd. to Hokitika	35,000	300	30	105	157·5
Hokitika to Pt. Elizabeth, Greymouth	48,000	200	30	96	144
Barrytown	10,000	400	40	53·3	80
Westport—					
Nine Mile Beach	12,000	300	30	36	54
Carters Beach	8,500	300	30	25·5	38·25
Karamea—					
Little Wanganui River to Kohaihai River	28,000	300	30	84	126
					869·6

for the average width and average depth of the sand deposits are open to correction, and could be determined accurately only by an extensive and costly drilling programme, such as would be necessary to delineate the economically exploitable portions of the deposits.

In assessing the average depths, the Department of Mines records of the dredging companies at Barrytown, Paroa, Waimea Creek, Saltwater Beach, Okarito, and Gillespie's Beach have been examined, and conservative figures taken, e.g., drill records for Barrytown Gold Dredging Co. Ltd. show blacksand at depths of 60 ft from the surface, whereas in Table 3 40 ft is taken for the average depth; at Gillespie's Beach drill records show blacksand at depths of over 50 ft from the surface, whereas the average depth taken in Table 4 is 40 ft; and at Okarito, dredging company records show blacksand to over 30 ft from the surface, whereas 30 ft is taken as the average depth.

The old dredges in the other localities mentioned all worked to depths of about 30 ft from the surface and, where depths are not known, 30 ft is considered to be a conservative figure.

DISCUSSION

As Tables 1 and 3 indicate, all the beaches north of the Haast River contain large tonnages of ilmenite. It is emphasized, however, that all the data given are for surface samples only, and the actual quantities of ilmenite available cannot even be conjectured until average samples over the full depth of the deposits are available. In assessing the possible resources even apparently low-grade areas, e.g., from Abut Head, south of Ross, to Point Elizabeth, north of Greymouth, have been considered. While not immeditely interesting for its ilmenite content, this whole locality also contains small amounts of magnetite, gold, and radioactive minerals, and some sections may possibly be worked at some future date for all the economic minerals.

The most important deposits, considering quantity and grade of material, ease of working, and accessibility, undoubtedly is that near Westport, extending south from the mouth of the Buller River a distance of some 12 miles. Carters and Nine Mile Beaches are estimated to contain some ninety odd million tons of sand, surface concentrates of which show 14% and 25% respectively of ilmenite.

Nineteen posthole bores, average depth 15 ft, by Marshall, Suggate, and Nicholson (1958) on the northern half of Nine Mile Beach showed that the surface sand above water level contained an average of 5·5% of magnetically recoverable ilmenite. In this locality should be mentioned also the Addisons Flat and Charleston raised beach deposits where there is known to exist some millions of cubic yards of blacksand which has been extensively worked for gold. A railway once connected the river harbour of Westport with the deposits north and south of Cape Foulwind and, rebuilt, could provide ready access for large-scale development.

Other possibly important deposits occur north of Haast River, at Bruce Bay, Gillespies Beach, Okarito, near Harihari, Barrytown, Karamea, but all lack access by rail and sea.

Table 2 shows the very important fact that these ilmenites are practically free of chromium and vanadium, and hence should be suitable for the production of titanium dioxide pigments.

References

Cox, S. H., 1881: Notes on the Mineralogy of New Zealand *Trans. N.Z. Inst. 14* : 418-50.

Gillson, J. L., 1949: "Industrial Minerals and Rocks", 2nd edit., pp. 1,066-7. The American Institute of Mining and Metallurgical Engineers, New York 1,156 pp.

Hutton, C. Osborne. 1945: The Titaniferous Ironsands of Patea, with an Account of the Heavy Residues in the Underlying Sedimentary Series. *N.Z. J. Sci. Tech., B21* : 190B-205B.

Marshall, T.; Suggate, R. P.; Nicholson, D. S., 1958: Borehole Survey of Ilmenite-bearing Beach Sands at Cape Foulwind, Westport. *N.Z. J. Geol. Geophys. 1* : 318-24.

Nicholson, D. S.; Fyfe, H. E., 1958: Borehole Survey of North Island Ironsands from New Plymouth to Kaipara Harbour. *N.Z. J. Geol. Geophys. 1* : 617-34.

Officer, V. C., 1947: A new Laboratory Magnetic Separator for Mineral Sands. *N.Z. J. Sci. Tech., B29* : 133-9.

Skey W., 1898: 33rd Annu. Rep. Colonial [N.Z.] Laboratory, p. 17.

BOREHOLE SURVEY OF NORTH ISLAND IRONSANDS FROM NEW PLYMOUTH TO KAIPARA HARBOUR

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Summary

A reconnaissance survey in 1949 indicates that on the beaches between the mouth of the Mokau River, 56 miles north of New Plymouth, and the township of Muriwai, 35 miles north-west of Auckland City, there is available over 600 million tons of magnetically recoverable ironsand assaying 58% Fe.

The most important deposit, that near Lake Taharoa, just south of Kawhia Harbour, contains some 173 million tons of ironsand in concentrations varying from 41% Fe in dune sands to 87% Fe in beach concentrates.

Introduction

Earlier records filed in the Department of Mines, and published work by Hutton (1940, 1945), Fleming (1946), Beck (1947), Finch (1947), had established quantities and grades of ironsand at Patea, Fitzroy, west of the Wanganui River, Waitara, and between the Wanganui and Whangaehu rivers, but no attempt had been made to assess the value of the many deposits along the coast north of New Plymouth. A committee of the Department of Scientific and Industrial Research decided that a survey of the ironsands north of New Plymouth should be made, and one of the authors (D.S.N.) was detailed to undertake this survey in collaboration with the New Zealand Geological Survey.

Preliminary Aerial Survey

An aerial survey of the coastline from Wanganui to the Kaipara Harbour was first made to give a preliminary assessment of the relative importance and accessibility of the different deposits and to provide a comparison of the quantities and grade of the sands with those areas already surveyed between Wanganui and Fitzroy, New Plymouth.

As a result of this survey it was decided that the following deposits warranted sampling. Waitara being included for comparison with previous work:

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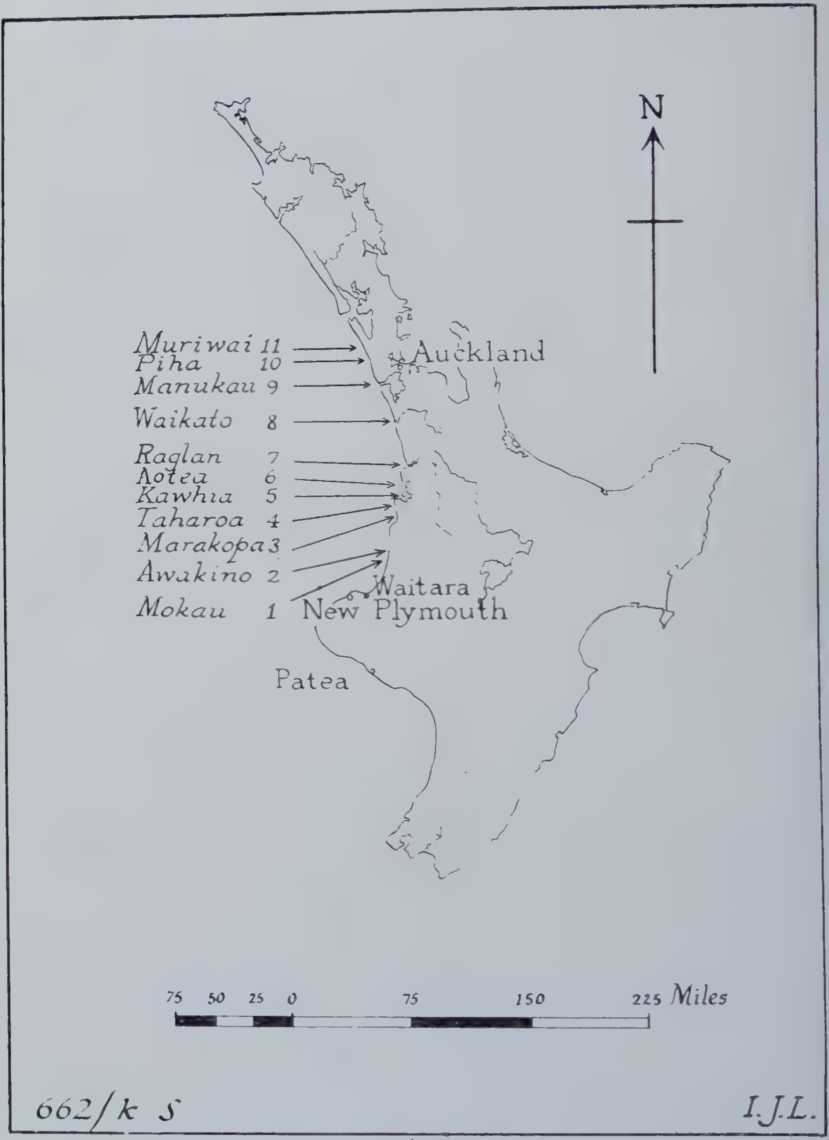


FIG. 1.—Locality map.

Waitara, Mouth of Mokau River, Mouth of Awakino River, Mouth of Marakopa River, Lake Taharoa, Kawhia Harbour, Raglan Harbour, Aotea Harbour, Waikato Heads, Manukau Heads, Piha, and Muriwai.

METHOD OF SAMPLING

Samples were taken with a 3 in. diameter posthole borer, which could be operated manually to a depth of about 25 ft but was difficult to handle efficiently at depths of more than 15 ft, and could not be used to obtain samples below water level.

On each deposit several scout holes were put down to obtain samples roughly representative of the whole deposit. Where deposits several hundred feet thick were encountered, a series of holes was drilled at increasing heights above sea-level.

The sand from each hole was collected on a canvas sheet, thoroughly mixed, and then reduced to about 20 lb by standard coning and quartering procedure. Where a relatively low dune of about 30 ft in height was being sampled, two holes each 15 ft deep were drilled on the side of the dune, one 15 ft above the other, and the samples combined as one sample representative of the full height of the dune.

The location of the holes is shown in Fig. 1, their approximate spot height above sea-level, their depth, and the percentage of magnetically separable ironsand in the samples are shown in Figs 2 to 11.

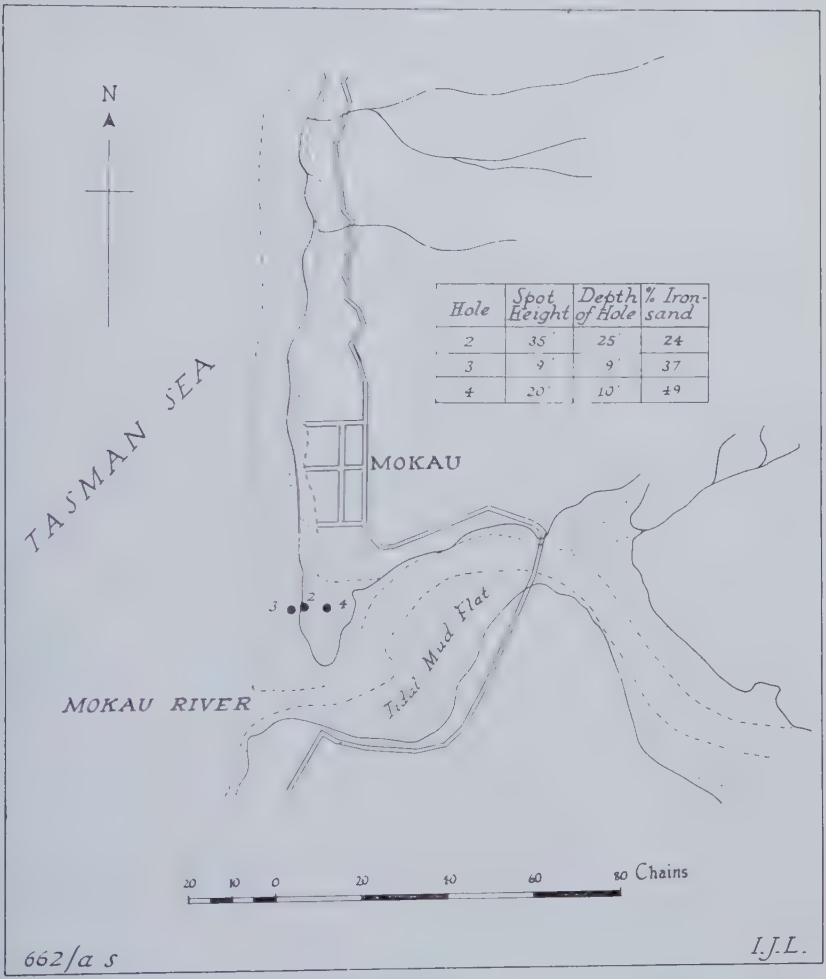
LABORATORY TREATMENT OF SAMPLES

The samples were dried and representative fractions of approximately 4 lb each were put through a wet Magnetic Separator (Martin, 1949) at Dominion Physical Laboratory. The magnetic field was adjusted until the resulting concentrate simulated what would be obtained on a practical scale, namely one having an iron content of about 58% which, on present information, is considered to be the maximum economic limit in iron content attainable by wet magnetic concentration. Individual concentrates, expressed as percentages by weight of the original material, are shown in Table 1.

TABLE 1.—Percentage of Magnetically Recoverable Ironsand.

Sample No.	Locality	Percentage of Magnetically Separable Ironsand (Approx. 58% Fe)
N1	Waitara, New Plymouth	19
N2	Mouth of Mokau River (Fig. 2)	24
N3	Mouth of Mokau River	37
N4	Mouth of Mokau River	49
N5	Mouth of Awakino River (Fig. 3)	63
N6	Mouth of Awakino River	65
N7	Mouth of Marakopa River (Fig. 4)	44
N8	Mouth of Marakopa River	57
N9	Mouth of Marakopa River	62
N10	Mouth of Marakopa River	51

Sample No.	Locality	Percentage of Magnetically Separable Ironsand (Approx. 58% Fe)
N11	Kawhia Hbr., north head (Fig. 6)	6
N12	Kawhia Hbr., north head	2
N13	Kawhia Hbr., north head	9
N14	Kawhia Hbr., north head	7
N15	Kawhia Hbr., north head	5
N16	Kawhia Hbr., north	0·6
N17	Kawhia Hbr., north head	6
N18	Kawhia Hbr., north head	11
N19	Kawhia Hbr., north head	13
N20	Kawhia Hbr., north head	28
N21	Lake Taharoa Area (Fig. 5)	41
N22	Lake Taharoa Area	45
N23	Lake Taharoa Area	87
N24	Lake Taharoa Area	61
N25	Lake Taharoa Area	81
N26	Lake Taharoa Area	71
N27	Raglan Hbr., north head (Fig. 8)	31
N28	Raglan Hbr., north head	14
N29	Raglan Hbr., north head	9
N31	Aotea Hbr., north head (Fig. 7)	6
N32	Aotea Hbr., north head	3
N33	Aotea Hbr., north head	5
N34	Waikato Heads, north side (Fig. 9)	7
N35	Waikato Heads, north side	9
N36	Waikato Heads, north side	5
N37	Manukau Heads, north side (Fig. 10)	46
N38	Manukau Heads, north side	25
N39	Manukau Heads, north side	21
N40	Piha area (Fig. 10)	9
N41	Piha area	6
N42	Piha area	60
N43	Piha area	31
N44	Piha area	12
N45	Muriwai (Fig. 11), south end, sample from seaward dune	41
N46	Muriwai, south end, 100 yds E of N45	12
N47	Muriwai, south end, 100 yds E of N46	38
N48	Muriwai, south end, 200 yds E of N47	18
N51	30 miles N of Muriwai, Kaipara sth head	0·8
N54	20 miles N of Muriwai, 6 ft section of seaward dune	0·3
N55	10 miles N of Muriwai, 10 ft section of seaward dune	0·5
N56	5 miles N of Muriwai, 20 ft section of seaward dune	0·6
N57	4 miles N of Muriwai, 30 ft section of seaward dune	0·9
N58	3 miles N of Muriwai, 30 ft section of seaward dune	2
N59	2 miles N of Muriwai, 15 ft section of seaward dune	10
N60A	1 mile N of Muriwai, 15 ft section of seaward dune	10
N60B	1 mile N of Muriwai, 150 yds E of N60A	13
N61A	½ mile N of Muriwai, 15 ft section of seaward dune	33
N61B	½ mile N of Muriwai, 200 yds E of N61A	13
N61C	½ mile N of Muriwai, 200 yds E of N61B	9
N61D	½ mile N of Muriwai, 400 yds E of N61C	22
Trig. XXX	Patea, at trig. station on top of dune	24



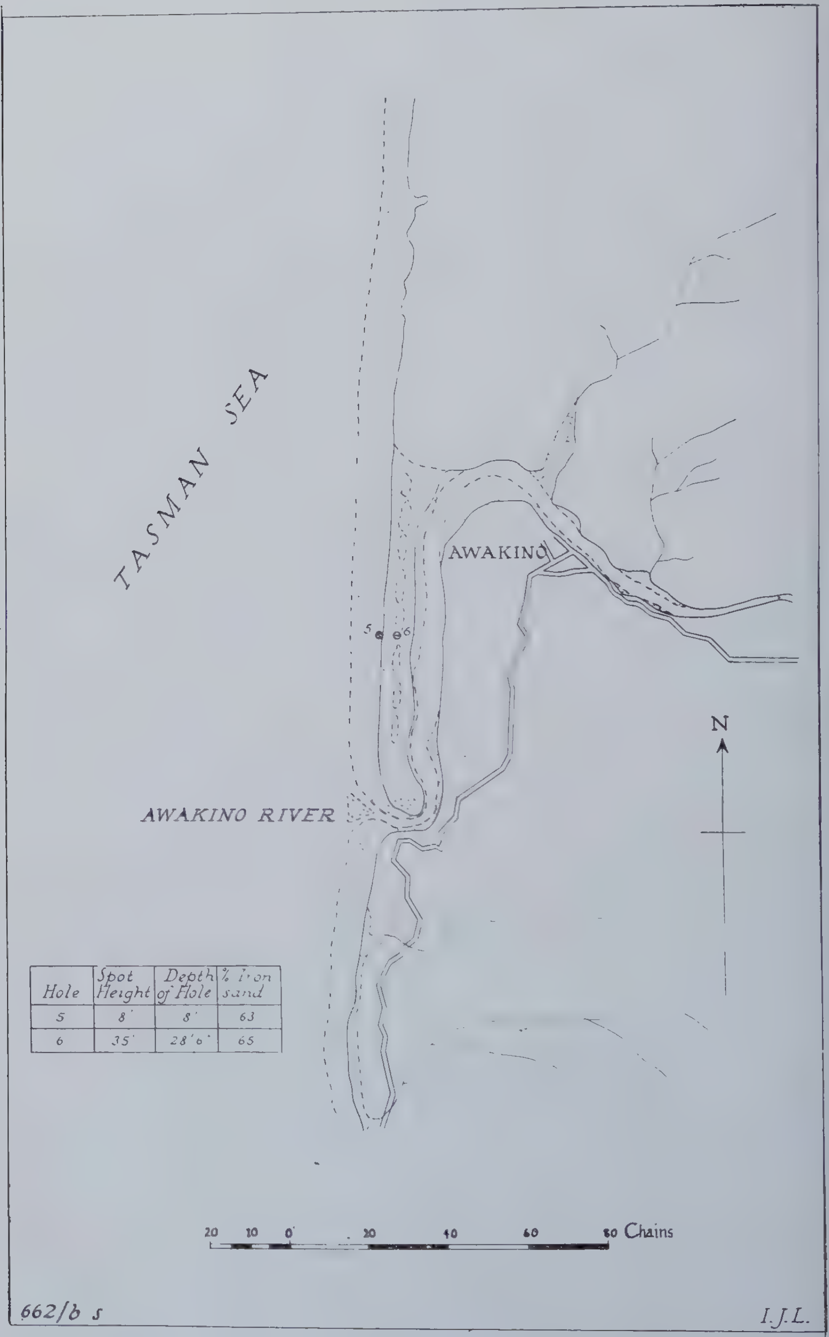
Hole	Spot Height	Depth of Hole	% Iron-sand
2	35′	25′	24
3	9′	9′	37
4	20′	10′	49

FIG. 2.

The final sample shown in Table 1, taken at Patea on the return journey to Wellington, is interesting in that it gives a comparison with typical Patea dune sand.

METHOD OF ASSESSING QUANTITIES OF SAND

To avoid lengthy and costly field work, it was considered sufficient for the purposes of a reconnaissance survey to compute roughly the quantities of sand in individual areas from contour plans prepared by the Aerial Survey Branch of the Department of Lands and Survey.

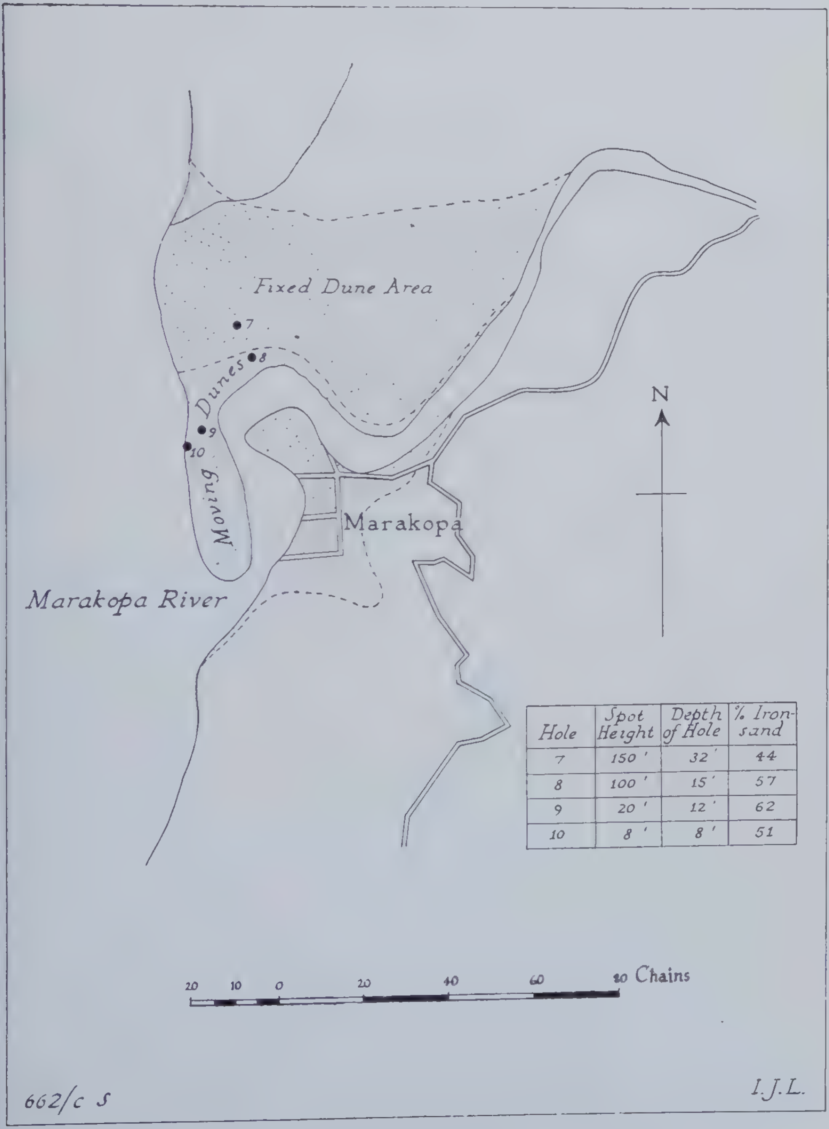


Hole	Spot Height	Depth of Hole	% Iron sand
5	8'	8'	63
6	35'	28'6"	65

FIG. 3.

These plans were contoured at 50 ft intervals from aerial photographs, control being given by sea-level and points that could be identified in the photographs and tied in with existing survey data.

Owing to lack of information about the possible extension of the ironsands below sea-level, only the quantities of sand above sea-level



Hole	Spot Height	Depth of Hole	% Iron-sand
7	150 '	32 '	44
8	100 '	15 '	57
9	20 '	12 '	62
10	8 '	8 '	51

FIG. 4.

have been computed, but in most of the areas surveyed further quantities of sand probably extend below sea-level, particularly in old lagoon or dune areas behind the present foreshore, e.g., Muriwai, Lake Taharoa.

The method of computation, though not very accurate, is sufficiently reliable to indicate the order of the quantities in the respective areas.

Areas within each contour line were measured by planimeter, and volumes of sand obtained by multiplying the average of two contour areas by the 50 ft interval between them. Tonnages of sand were calculated by taking 1 cu. yd. of sand at 1·5 tons.

The smaller deposits and the low-lying ones did not warrant obtaining contoured plans, and for these the area was measured by planimeter from New Zealand Geological Survey field plans, and an average depth of sand was assessed from field notes.

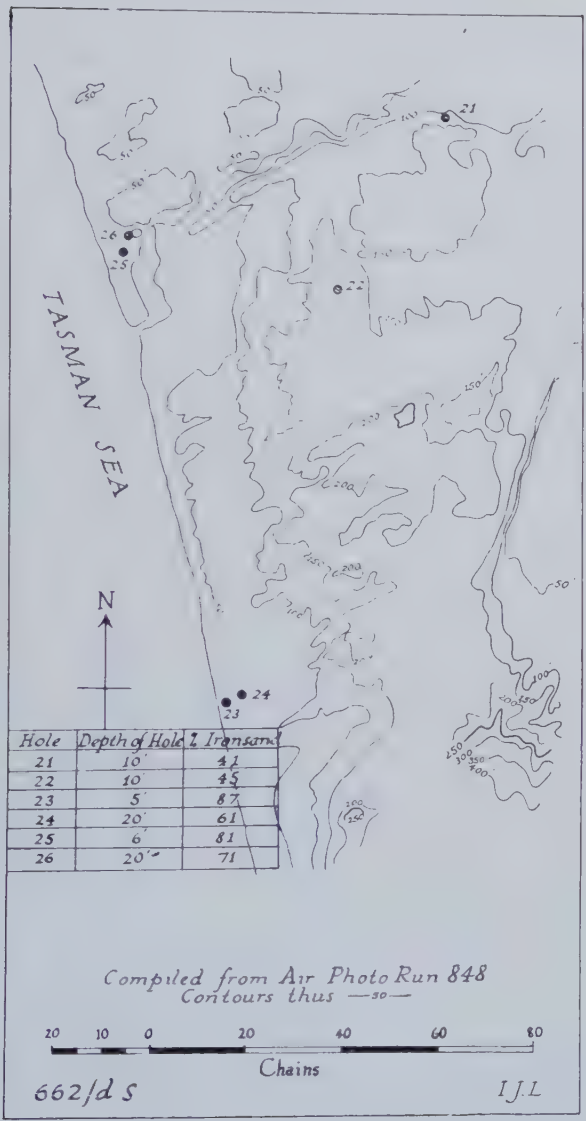
Volumes and tonnages of total sand and recoverable ironsand for each area are shown in Table 2.

It is emphasized that the figures given for recoverable ironsand indicate merely the order of the quantities, as it will be obvious that insufficient samples were taken for reliable figures to be given for the average percentage of recoverable ironsand in each area.

TABLE 2.—Quantities of Ironsand.

	Total Quantity of Sand		Recoverable Ironsand (approx. 58% Fe)	
Locality	Cu. yd $\times 10^6$	tons $\times 10^6$ (1 cu. yd = 1·5 tons)	Average % in samples taken	Tons $\times 10^6$
Mokau	7·0	10·5	37	3·9
Awakino	6·0	9·0	64	5·8
Marakopa	36·62	54·93	53	29·1
Lake Taharoa	274·20	411·3	64*	263·2*
Kawhia Hbr.-N. Head	1.367·01	2,050·5	9	184·5
Aotea Hbr.-N. Head	333·51	500·26	5	25·0
Raglan Hbr.-N. Head	323·63	485·45	18	87·3
Waikato Heads	854·49	1,281·73	7	89·7
Manukau Hbr.-N. Head	11·3	17·0	31	5·3
Piha	2·3	3·45	24	0·8
Muriwai (2 ml south end)	58·54	87·8	20	17·6

*The authors consider that the figure of 64% for the average percentage of recoverable ironsand (the arithmetic mean of the figures given for the six drill hole results shown on the plan of the locality) is much too high for assessment purposes as it is unduly weighted by the high results of the four samples taken near the present beach An average percentage of 42%, giving an estimated tonnage of ironsand concentrate of $172{\cdot}7 \times 10^6$ tons, is considered to be a more realistic and conservative estimate.

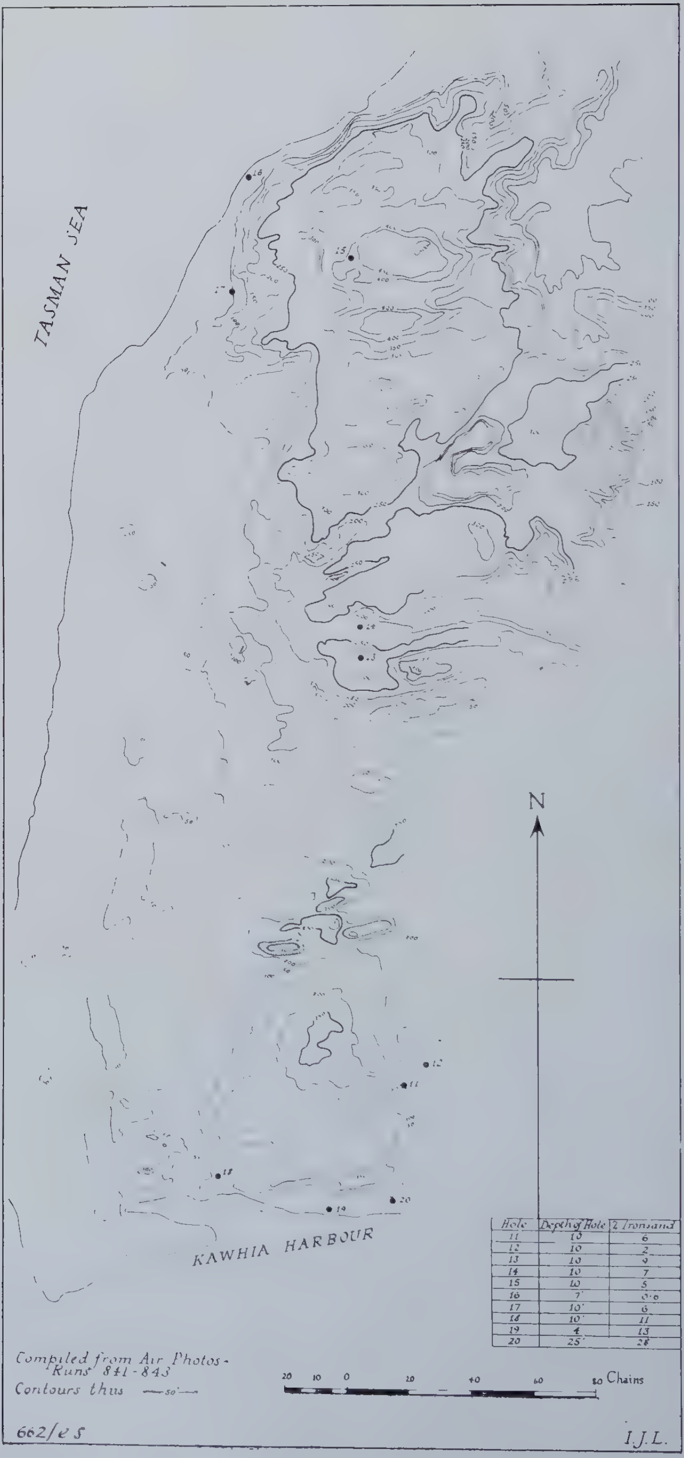


Hole	Depth of Hole	% Ironsand
21	10'	41
22	10'	45
23	5'	87
24	20'	61
25	6'	81
26	20'	71

FIG. 5.—Lake Taharoa area.

OTHER LOCALITIES NOT SAMPLED

In this section can be included deposits between Wanganui and New Plymouth observed during the aerial survey, but which have not yet been surveyed for the quantity or quality of their ironsand. It is considered that the areas mentioned warrant investigation in the final assessment of New Zealand ironsands resources.



Hole	Depth of Hole	% Ironsand
11	10	6
12	10	2
13	10	9
14	10	7
15	10	5
16	7'	0·0
17	10'	6
18	10'	11
19	4	13
20	25'	28

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FIG. 6.

West of the area reported on by Fleming (1946), between the Waitotara and Patea rivers, is an extensive area between the railway line and the coast which is covered by sand, partly as active dunes along the coast, but mostly under pasture. A large part of this area along the coastline could be worked without encroaching on better farm areas inland, though measures to prevent landward migration of dunes might be necessary.

West of the Patea deposits investigated by the Department of Mines and by Hutton (1940) is an area of dunes generally about a mile wide but narrowing towards Hawera. Apart from the narrow coastal strip, most of this dune area is under pasture.

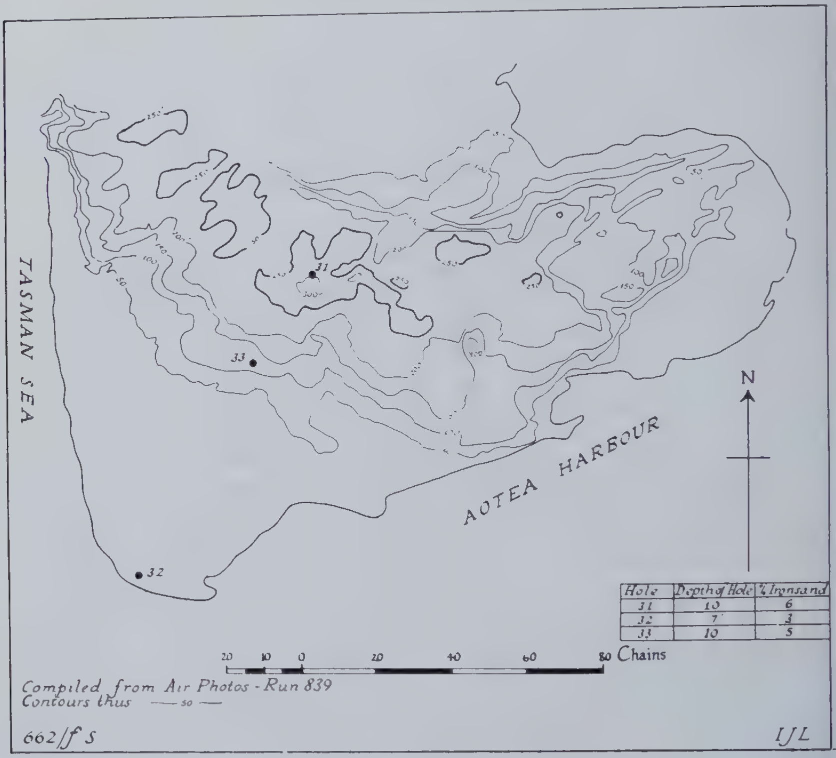
North of New Plymouth, apart from the areas sampled, are the following small areas on which the ironsand appeared from the air survey to be of high grade, but because of their inaccessibility and small size they were considered not worth sampling at present:

The beaches at Urenui and Waitoitoi, small areas at the mouths of the Tongaporutu and Mohakatino rivers, the beach at Whareorino, the beach in the bay north of Tirua Point. Much farther north, between Piha and Muriwai, is a small area at Bethells.

GENERAL DISCUSSION OF DEPOSITS

Table 2 indicates that the Lake Taharoa area is potentially the most important deposit and field evidence confirms this, though access to the area is difficult, either by land or sea. Deep drilling will be necessary to prove this deposit but from surface evidence and the samples taken it contains a vast quantity of high-grade ironsand. An indication of the potential importance of the deposit is given by comparing it with that at Patea, where, according to records of the Department of Mines, there are 14,000,000 tons of potential concentrate assaying 53·4% soluble Fe (Mason, 1945). The Taharoa deposit contains about 173 million tons assaying 58% soluble Fe.

The next deposit in order of potential importance is that at Muriwai, where the southernmost two miles of beach and dune area above sea-level contains some 17·6 million tons of recoverable ironsand, of 20% grade. Evidence of subsidence indicates the probable extension of the ironsand below sea-level, an important factor in this locality, as other conditions are suitable for mining by bucket or suction dredging, the most economical method known. If the sand persists to a depth of about 30 ft below mean sea-level, which on geological evidence seems probable, this method of mining and concentration could be applied, and a preliminary concentrate containing some 58% Fe could be produced at very low cost per ton. Drilling below water level would be necessary to prove the depth If the ironsand persists to a depth of 30 ft below mean sea-level, the quantity of recoverable iron ore would be nearly twice the figure given in Table 2.



Hole	Depth of Hole	% Ironsand
31	10	6
32	7	3
33	10	5

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Fig. 7.

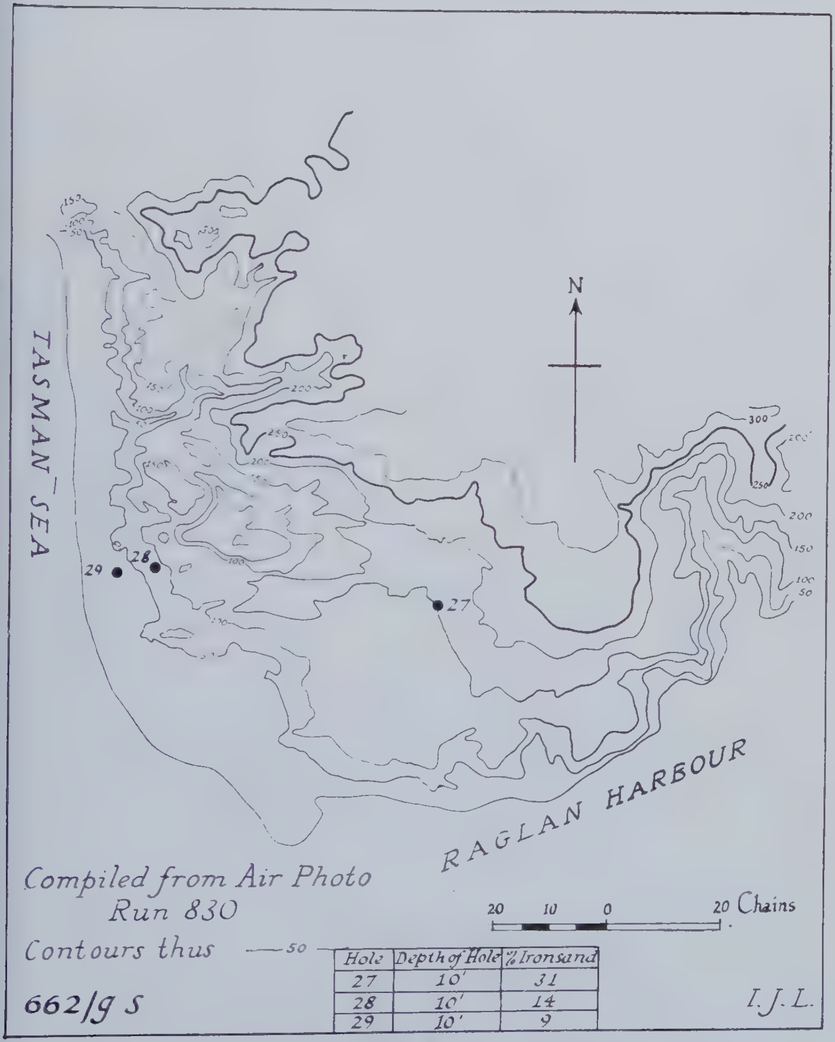
Probably next in order of potential importance is the deposit at the mouth of the Marakopa River, where there are some 29 million tons of recoverable ironsand of 53% grade. Though larger and of higher grade than the Muriwai deposit it is considered by the writers to be not so important economically because of the greater difficulty of access and the fact that the deposit is not suitable for mining by dredging. Mining and transport costs would therefore be much higher than for Muriwai.

The small deposits at the mouth of the Mokau and Awakino rivers are also high grade in comparison with the Patea deposit, and here again inaccessibility and small size may prevent development.

The huge sand deposits in the Kawhia, Aotea, and Raglan harbour areas, as well as that at Waikato Heads, are low in ironsand content, and it is doubtful if they will ever warrant development.

The quantity of recoverable ironsand at Piha is too small to warrant much consideration, and as the locality is developing as a seaside rsort it is unlikely that mining of ironsand would be permitted.

Comparing the areas surveyed with the better known ironsand areas between Wanganui and New Plymouth, it would seem that generally the grade of the ironsand is higher to the north than to the south of New Plymouth. Access, both by land and sea, to the deposits south of New Plymouth is considerably better than to the northern deposits. Generally, the northern deposits do not form such good farming land as the southern ones. In any area to be worked, consideration would have to be given to the regeneration of vegetation in order to combat serious sand drift. At Muriwai and Waikato Heads, if these areas were worked, the expense of reafforestation would have to be considered.



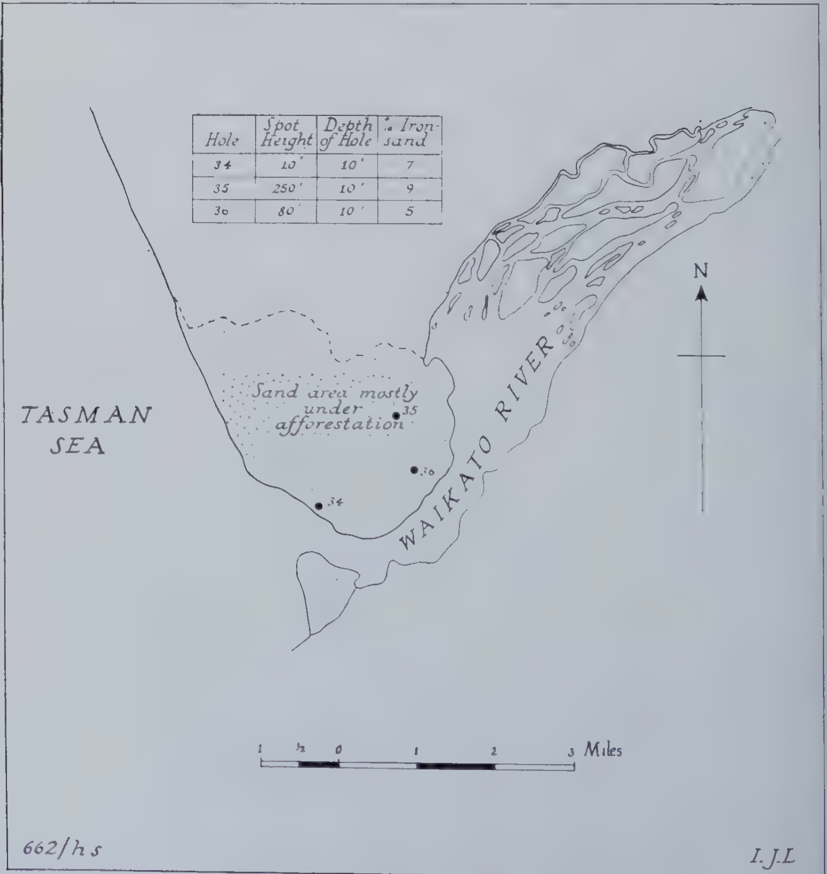
Hole	Depth of Hole	% Ironsand
27	10′	31
28	10′	14
29	10′	9

FIG. 8.

To facilitate comparison of the northern with the southern areas, figures available for the areas between Wanganui and New Plymouth are shown in Table 3.

TABLE 3.—Quantitative Figures available from Previous Work.

Locality	Total Sand (tons) (approx.)	Titanomagnetite Concentrate (tons) (approx.)
Waitara, New Plymouth (Beck, 1945)	31,469,000	7,687,000
Fitzroy, New Plymouth (Hutton, 1945)	1,120,000	500,000
Patea (Mason, 1945)	45,000,000	14,000,000 (53·4% Fe)
West of Wanganui (Fleming, 1946)	143,355,000	22,807,345
Wanganui-Whangaehu (Finch, 1947)	69,600,000	Very low grade; doubtful if worth working.



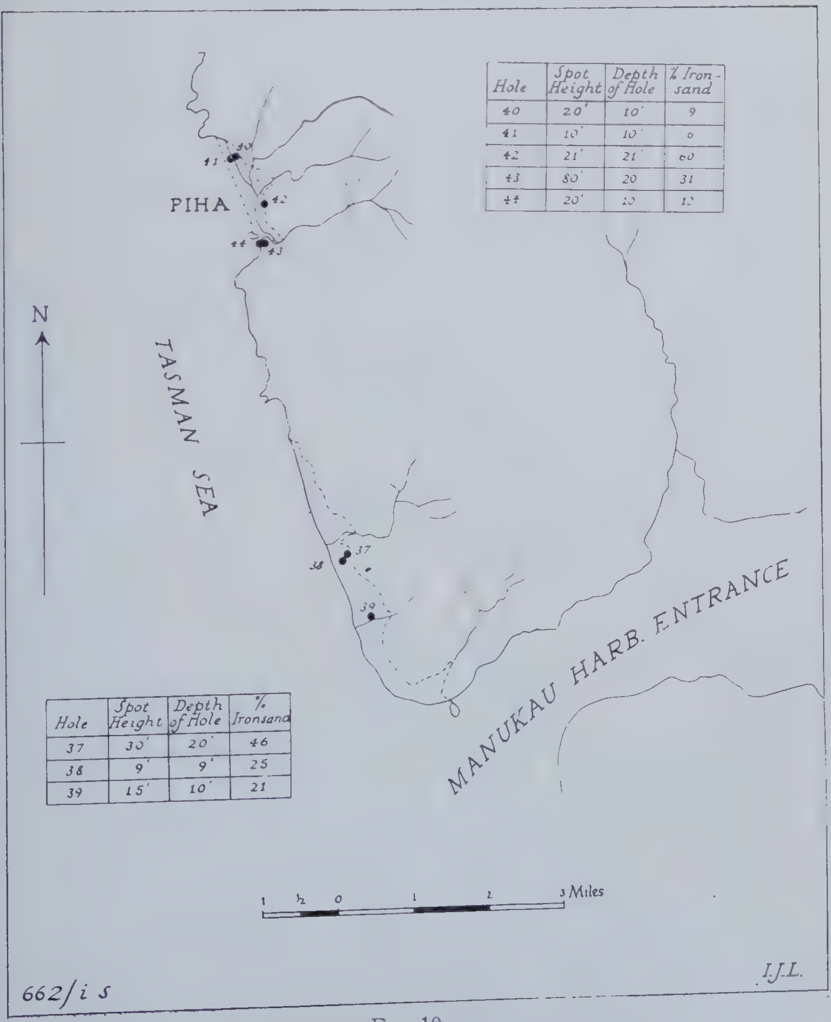
Hole	Spot Height	Depth of Hole	% Iron-sand
34	10'	10'	7
35	250'	10'	9
36	80'	10'	5

FIG. 9.

Deposits Considered as Possible Sources of Ilmenite

Though the main consideration in this paper, is the assessment of North Island ironsands as a source of iron and steel, with possible by-product titanium and vanadium, it should also be pointed out that some deposits contain ilmenite, possibly important as a source of titanium and its compounds, with by-product iron.

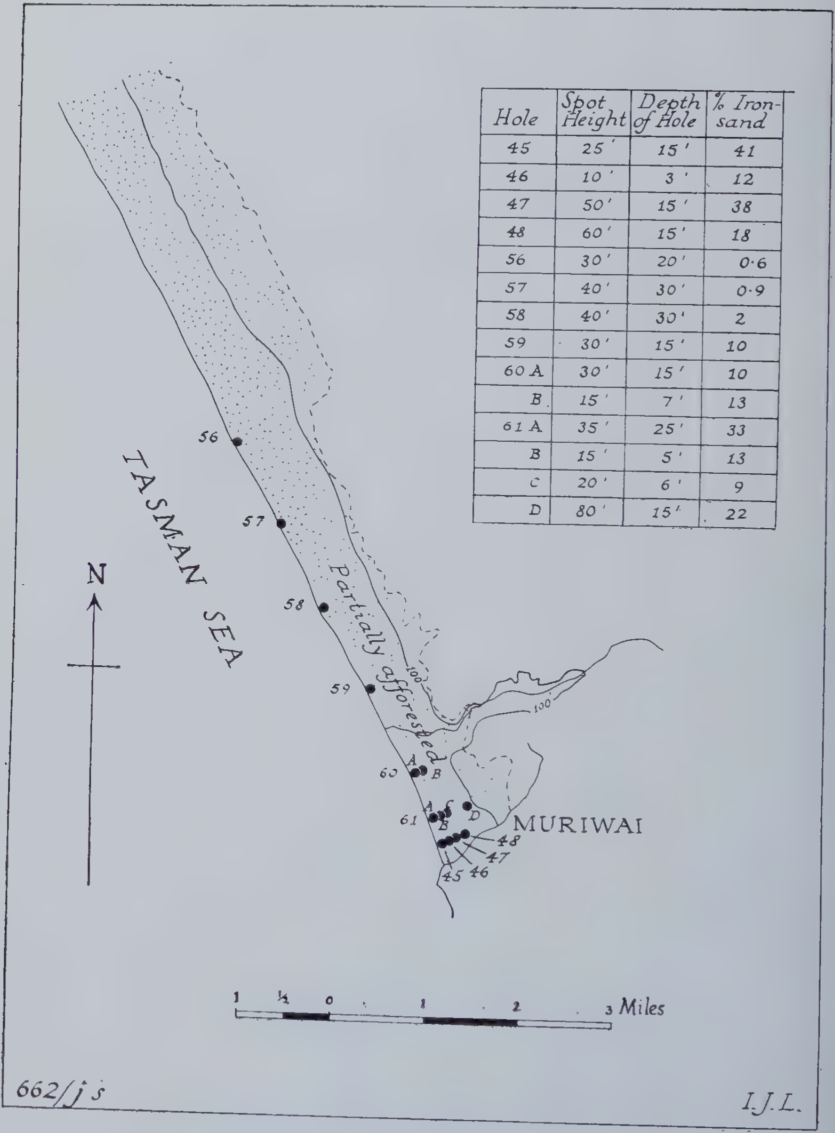
For many years it has been known that the main mineral of most North Island ironsand deposits is titanomagnetite, containing some



Hole	Spot Height	Depth of Hole	% Ironsand
40	20′	10′	9
41	10′	10′	0
42	21′	21′	60
43	80′	20	31
44	20′	10	12

Hole	Spot Height	Depth of Hole	% Ironsand
37	30′	20′	46
38	9′	9′	25
39	15′	10′	21

FIG. 10.



Hole	Spot Height	Depth of Hole	% Iron-sand
45	25'	15'	41
46	10'	3'	12
47	50'	15'	38
48	60'	15'	18
56	30'	20'	0·6
57	40'	30'	0·9
58	40'	30'	2
59	30'	15'	10
60 A	30'	15'	10
B	15'	7'	13
61 A	35'	25'	33
B	15'	5'	13
C	20'	6'	9
D	80'	15'	22

FIG. 11.

58% iron, 5% titanium, and 0·2% vanadium, important as a source of iron. Only comparatively recently has it been known that ilmenite, containing some 27% titanium and 32% iron, occurs in some North Island deposits (Nicholson *et al.*, 1958).

All samples taken on the present survey were examined for their ilmenite content by Mr J. J. S. Cornes and Dr J. Finch of Dominion Laboratory. Samples, from which the titanomagnetite had been removed by Mr J. Mautner at Dominion Physical Laboratory by wet magnetic separation, were subjected to dry magnetic separation by Mr Cornes to give ilmenite concentrates. Grain counts of the concentrates were made by Dr Finch to give approximate percentages of ilmenite. Results are shown in Table 4.

TABLE 4.—Percentages of Ilmenite.

Sample Number	Locality	Approx. Percentage of Ilmenite
N.34	Waikato Heads	0·2
N.35	Waikato Heads	1·5
N.36	Waikato Heads	0·2
N.37	Manukau Heads	16·9
N.38	Manukau Heads	6·6
N.39	Manukau Heads	2·8
N.40	Piha	3·4
N.41	Piha	3·5
N.42	Piha	12·1
N.43	Piha	6·8
N.44	Piha	3·0
N.45	Muriwai south end	11·0
N.46	Muriwai south end	6·5
N.47	Muriwai south end	8·2
N.48	Muriwai south end	7·1
N.51	Kaipara Hbr. south head	2·7
N.54	20 miles north of Muriwai	0·01
N.55	10 miles north of Muriwai	0·08
N.56	5 miles north of Muriwai	0·05
N.57	4 miles north of Muriwai	0·2
N.58	3 miles north of Muriwai	0·8
N.59	2 miles north of Muriwai	3·5
N.60A	1 mile north of Muriwai	3·1
N.60B	1 mile north of Muriwai	1·8
N.61A	½ mile north of Muriwai	7·4

Table 4 shows that the Muriwai (south end) and Manukau Heads deposits, as well as being potentially important as sources of titanomagnetite for iron and steel, may assume some importance as potential sources also of ilmenite for titanium and iron. In the future this may be a strong factor in favour of developing these deposits in preference to some of the more southerly ones.

It will also be noted that ilmenite occurs only in deposits north of the mouth of the Waikáto River.

It should be pointed out that North Island ilmenites are similar to the South Island ones (see Nicholson *et al.*, 1958) in that they have a low

TiO_2 content when compared with important overseas sources of titanium-bearing sands. This is shown in the following table.

TABLE 5.—Comparison of New Zealand and Foreign Ilmenites.

Locality	Percentages			
	Fe	TiO_2	V_2O_5	Cr_2O_3
*Manukau Heads, Auckland	39·9	42·5	0·15	0·02
*Nine Mile Beach, Westport	32·5	45	$<$ 0·05	$<$ 0·01
Pure ilmenite $FeO \cdot TiO_2$	36·8	52·7	Nil	Nil
Pure 'arizonite' $Fe_2O_3 \cdot 3TiO_2$	28·0	60·0	Nil	Nil
Foreign Ilmenites (Gillson, 1949)				
†Travancore (India) "Quilon"	24·7	60·4	0·36	0·17
†Jacksonville, Florida, U.S.A.	22·7	60·3	N.D.	N.D.

*From Dominion Laboratory unpublished reports.
†These are 'arizonites', but are marketed as ilmenites.

REFERENCES

BECK, A. C., 1947: Ironsands at Waitara, New Plymouth. *N.Z. J. Sci. Tech. B28* : 307-13.

FINCH, J., 1947: The Wanganui-Whangaehu Ironsands. *Ibid. B29* : 36-51.

FLEMING, C. A., 1946: Magnetic Ironsands, West of Wanganui. *Ibid. B27* : 347-65.

GILLSON, J. L., 1949: Industrial Minerals and Rocks. 2nd edit., pp. 1,066-7. The American Institute of Mining and Metallurgical Engineers, New York. 1,156 pp.

HUTTON, C. OSBORNE, 1940: The Titaniferous Ironsands of Patea, with an Account of the Heavy Residues in the Underlying Sedimentary Series. *Ibid. B21* : 190-205.

———, 1945: The Ironsands of Fitzroy, New Plymouth. *Ibid. B26* : 291-302.

MARTIN, W. R. B., 1949: A Laboratory Wet Magnetic Separator for Strongly Magnetic Mineral Sands. *Ibid. B31* : 5-21.

MASON, BRIAN, 1945: The Utilization of New Zealand Ironsands as a Source of Iron, Titanium, and Vanadium. *Ibid. B26* : 227-38.

NICHOLSON, D. S.; CORNES, J. J. S.; MARTIN, W. R. B., 1958: Ilmenite Deposits in New Zealand. *N.Z. J. Geol. Geophys. 1* : 611-6.

ADDITIONAL DATA ON THE VOLCANIC ARGILLITES FROM RED ROCK POINT, WELLINGTON

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(Received for publication, 25 July 1958)

Summary

The dove-grey volcanic argillite from Red Rock Point is petrographically and chemically very similar to the red and green volcanic argillites, and differs only in the degree of oxidation of the iron oxide. These volcanic argillites are considered to be mainly argillaceous in nature (at least 70 to 80%), with the admixture of volcanic material probably containing a high proportion of finely divided iron oxide.

Introduction

The accessible and well exposed sequence of volcanic rocks intercalated with the Wellington greywackes and argillites at Red Rock Point has been described by several geologists (McKay, 1879, 1888; Broadgate, 1916; Wellman, 1949; Brodie, 1953). A petrographic account has recently been provided (Reed, 1957) but no chemical data was then available on the dove-grey argillite which forms an important member of the volcanic sequence. The purpose of this paper is to present a chemical analysis of this argillite and to discuss the origin of the volcanic argillites in the light of this new knowledge.

Occurrence and Petrography

The volcanic sequence at Red Rock Point is shown in the accompanying rock-column (Fig. 1), and the high proportion of dove-grey argillite will be noted. Except for the colour, the argillite is petrographically identical to the red and green (green-grey) volcanic argillites. All are poorly bedded with an incipient slaty cleavage, and display a distinctive micro-texture in thin section (Fig. 2). This micro-texture, a combination of uniform fine grain-size and slaty cleavage, contrasts markedly with that of the normal argillite (silt-wacke) of the Wellington district (Reed, 1957).

Chemical Composition

A chemical analysis of a sample (P 15888), collected from about the middle of the dove-grey argillite at Red Rock Point, is given in Table 1. The analysis is very similar to that of the red and green volcanic argillites (Reed, 1957; Table 5), as is indicated in Fig. 3. In all samples

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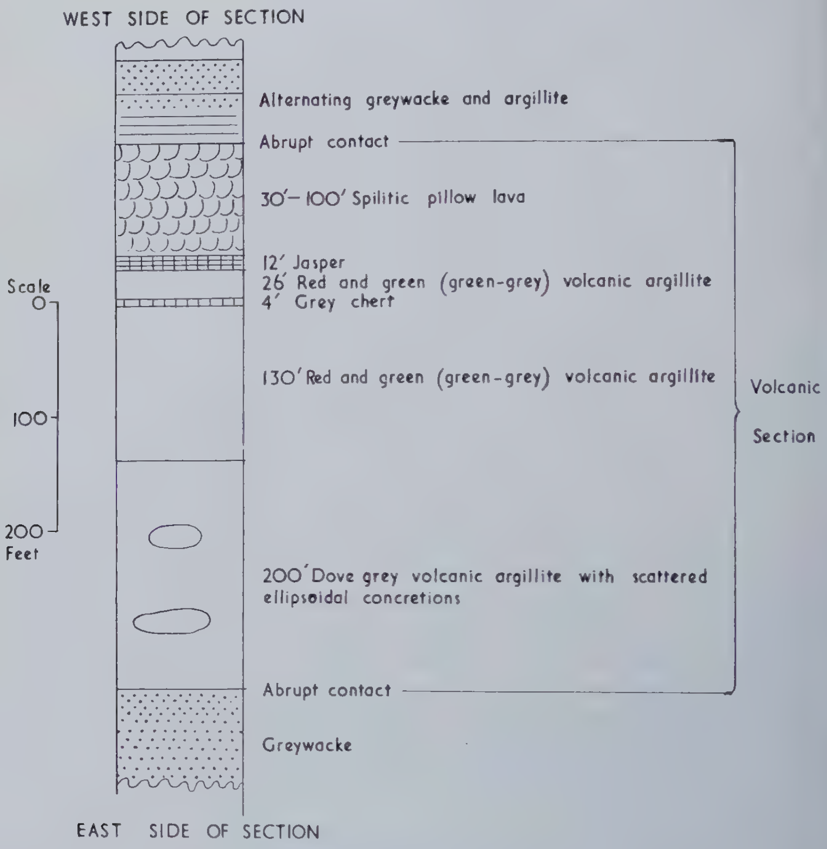
WEST SIDE OF SECTION
Alternating greywacke and argillite
Abrupt contact
30'–100' Spilitic pillow lava
12' Jasper
26' Red and green (green-grey) volcanic argillite
4' Grey chert
Scale
0
100
200
Feet
130' Red and green (green-grey) volcanic argillite
Volcanic Section
200' Dove grey volcanic argillite with scattered ellipsoidal concretions
Abrupt contact
Greywacke
EAST SIDE OF SECTION

FIG. 1.—Rock Column showing volcanic section at Red Rock Point (after Wellman, 1949, and Reed, 1957).

the total amount of iron is approximately constant, differences in coloration being due to different degrees of oxidation of the iron (see Fig. 4; Table 2).

DISCUSSION

One of the main problems with the volcanic argillites is to determine the proportion of argillaceous sediment to volcanic material. The composition of the volcanic argillites lies between that of the Wellington argillites and spilitic lavas, but much nearer the former (Fig. 3). This does not mean simple admixture of the two, however, for as pointed out elsewhere (Reed, 1957, p. 42), the distinctive micro-texture of the volcanic argillites indicates that they are admixtures, not of the normal argillite but of a finer-grained sediment, either a clay-wacke

TABLE 1.—Chemical Analysis of Dove-grey Volcanic Argillite from Red Rock Point, Wellington.

		Molecular Norm	
SiO_2	59·8	Q = 20·3	Salic = 81·4
Fe_2O_3	18·0	or = 21·5	Femic = 18·7
Al_2O_3	0·7	ab = 26·0	
FeO	5·65	an = 4·0	
MgO	2·9	C = 9·6	
CaO	1·0	en = 7·6	
Na_2O	2·7	fs = 8·6	
K_2O	3·5	il = 1·2	
Li_2O	Nt fd	mt = 0·8	
H_2O+	3·9	ap = 0·5	
H_2O-	0·2		
TiO_2	0·76		
P_2O_5	0·28		
MnO	0·10		
CO_2	Nt fd		
Total:	99·5		

Dove-grey volcanic argillite (P 15888) from Red Rock Point, Wellington (N.Z.M.S. 1 Sheet N164, grid ref. 292133).
Analyst: J. A. Ritchie, Dominion Laboratory, D.S.I.R.

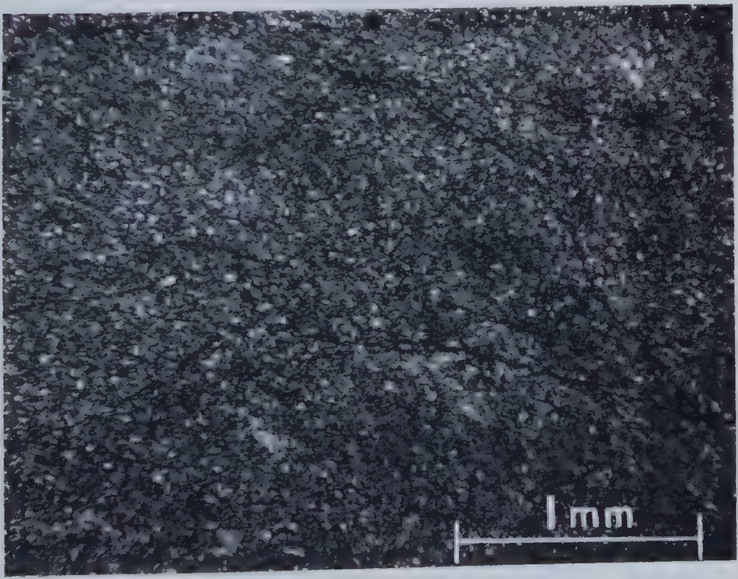

FIG. 2.—Photomicrograph of dove-grey volcanic argillite from Red Rock Point showing characteristic micro-texture.
Photo: A. V. Weatherhead.

or deep-water lutite. Support for this conclusion is provided by the alumina content, which in the volcanic argillites is significantly higher than in both the normal argillite and the spilitic lava (Table 3). There

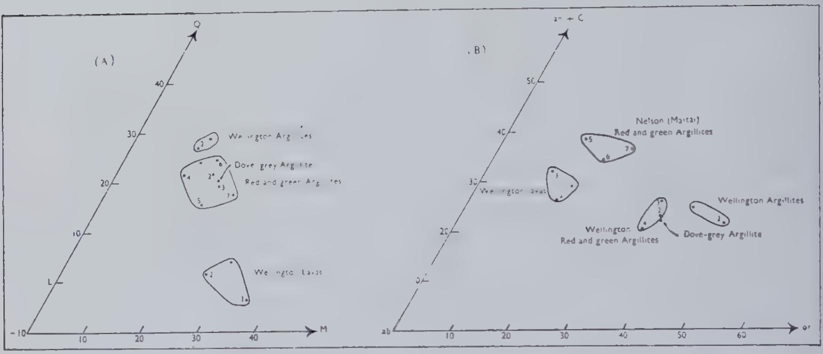

FIG. 3.—Diagrams showing close similarity in composition between the dove-grey and the red and green volcanic argillites from Red Rock Point (after Reed, 1957, Fig. 34).

TABLE 2.—Normative Magnetite in Volcanic Argillites from Red Rock Point, Wellington.

	Dove-grey	Green	Red
mt	0·8	2·3	4·2
		1·5	2·3

are no chemical data on this inferred sediment, but if the analysis of the composite sample of Wellington argillites (Reed, 1957: Table 3, Column 1) is assumed to provide a reasonable indication of its composition, then the theoretical proportions of the various major constituents

TABLE 3.—Comparison of the major constituents in the volcanic argillites, spilitic lavas and normal argillites (compare Reed, 1957).

	(1)	(2)	(3)	(4)
SiO_2	48·21	60·53	64·2	23
Al_2O_3	15·25	18·02	16·3	—
Fe_2O_3	5·89	2·01	0·72	25
FeO	5·09	4·88	4·1	79
MgO	3·12	2·55	1·9	53
CaO	8·05	1·04	1·4	—
Na_2O	4·02	2·83	2·2	35
K_2O	1·58	3·46	3·7	11
TiO_2	1·80	0·81	0·70	10
MnO	0·28	0·14	0·06	36

(1) Average spilitic lava.
(2) Average volcanic argillite.
(3) Average Wellington argillite.
(4) Theoretical Proportion of the various major constituents of the spilitic lava required to be mixed with the Wellington argillite to produce the volcanic argillite.

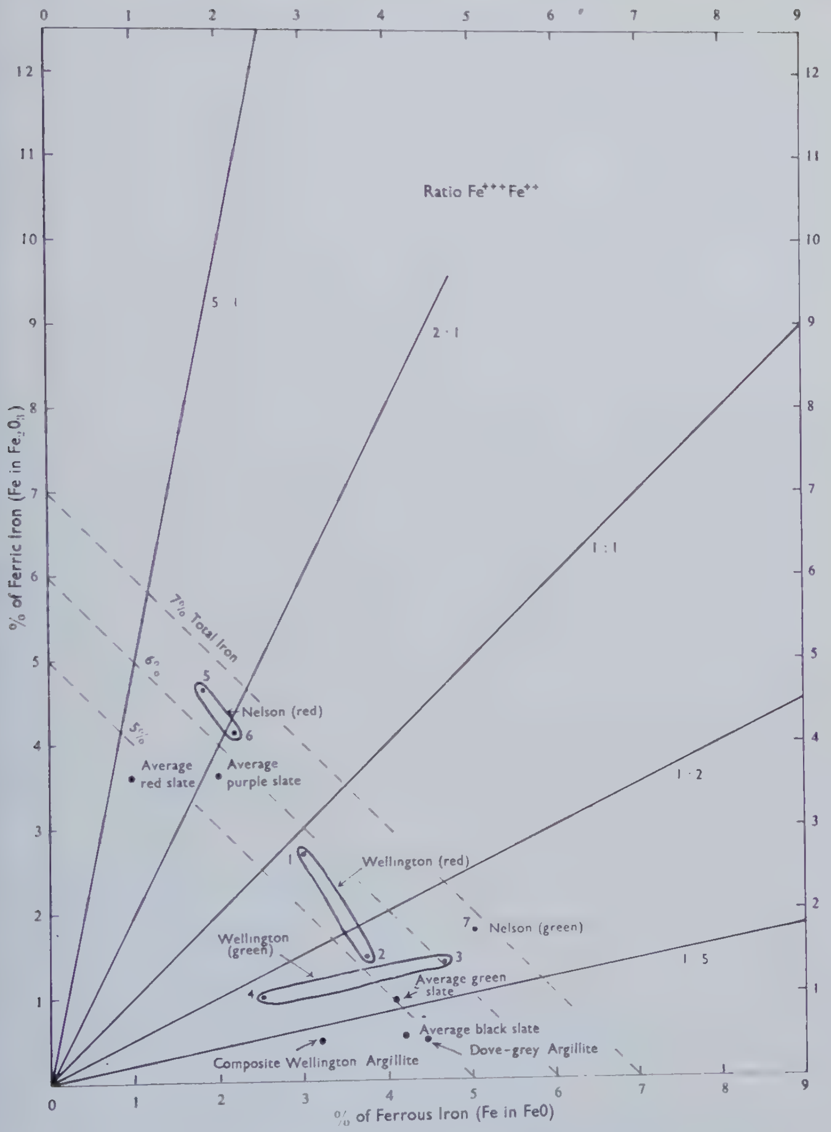

FIG. 4.—Diagram showing proportion of ferrous to ferric iron in dove-grey volcanic argillite from Red Rock Point and in analysis of composite Wellington argillite sample (after Reed, 1957, Fig. 35).

of the spilitic lava required to be mixed with the Wellington argillite to produce the volcanic argillite are indicated in Table 3. The low CaO value in the volcanic argillite is possibly due to concentration of the lime in concretions. The micro-texture of the volcanic argillites demonstrates that the volcanic material is of a uniform fine-grain size, and judging from Table 3 iron oxide is a prominent addition.

Consideration of the evidence suggests that the volcanic argillites are largely argillaceous in nature (at least 70 to 80 per cent.) and that the admixture of volcanic material probably contains a high proportion of finely divided iron oxide.

REFERENCES

BROADGATE, R. K., 1916: The "Red Rocks" and Associated Beds of Wellington Peninsula. *Trans. roy. Soc. N.Z. 48* : 76-86.

BRODIE, J. W., 1953: Stratigraphy and Structure of the Greywackes and Argillites on the South Coast of Wellington Peninsula. *N.Z. J. Sci. Tech. B 34* : 205-26.

MCKAY, A., 1879: The Geology of the Neighbourhood of Wellington. *N.Z. geol. Surv. Rep. geol. Explor. 1878-9, 12* : 131-5.

———, 1888: On the Tauherenikau and Waiohine Valleys, Tararua Range. *Ibid. 1887-8, 19* : 1-6.

REED, J. J., 1957: Petrology of the Lower Mesozoic Rocks of the Wellington District. *N.Z. geol. Surv. Bull. n.s. 57.*

WELLMAN, H. W., 1949: Pillow Lava at Red Rock Point, Wellington. *Trans. roy. Soc. N.Z. 77* : 306-12.

OCCURRENCE OF STERRASTERS OF THE GEODIIDAE (DEMOSPONGEA, CHORISTIDA) IN LATE CENOZOIC STRATA OF WESTERN WELLINGTON PROVINCE, NEW ZEALAND

By Charles C. Rich, Bowling Green State University, Bowling Green, Ohio

(Received for publication, 6 August 1958)

Summary

Sterrasters, the microsclere siliceous spicules of certain marine sponges, have been recognized in strata ranging from Upper Miocene to Pleistocene in age, including some beds of the Pleistocene Hawera Series previously considered to be non-marine. The sterrasters are described and compared with those of modern and fossil sponges from the New Zealand region. The genus *Geodia* Lamarck is definitely represented by the sterrasters examined, but the presence of other genera of the family Geodiidae cannot be ruled out. Attention is drawn to the usefulness of sterrasters as indicators of marine deposition, and it is suggested that these structures may be widespread in the Upper Cretaceous and Cenozoic "covering strata" of New Zealand.

Introduction

Hitherto unidentified minute organic bodies, termed "silicaliths" by Te Punga (1954), were observed in microfaunal preparations made in connection with stratigraphic studies in the lower Manawatu Valley of western Wellington Province. The sediments examined range in age from Upper Nukumaruan to Hawera (Lower to Upper Pleistocene), but Dr Te Punga has informed the writer (pers. comm.) that strata of the neighbouring Rangitikei district from which he has extracted these structures range in age from Kapitean (Upper Miocene) to Hawera. Invariably the "silicaliths" were observed to be associated with megasclere spicules of sponges, although other microfaunal remains are commonly also present. Microscopic study of these bodies has shown them to be sponge microscleres, or so-called "flesh spicules", of the type termed *sterrasters*.

Description

Ellipsoidal in shape, some nearly spherical in outline (Fig. 1), a few are almost prolate spheroids, but most show a definite equatorial flattening defining two sides. At the centre of one side is a nearly circular pit or depression, the umbilicus. Preliminary measurements indicate that the greatest dimension ranges from 0·12 mm to almost

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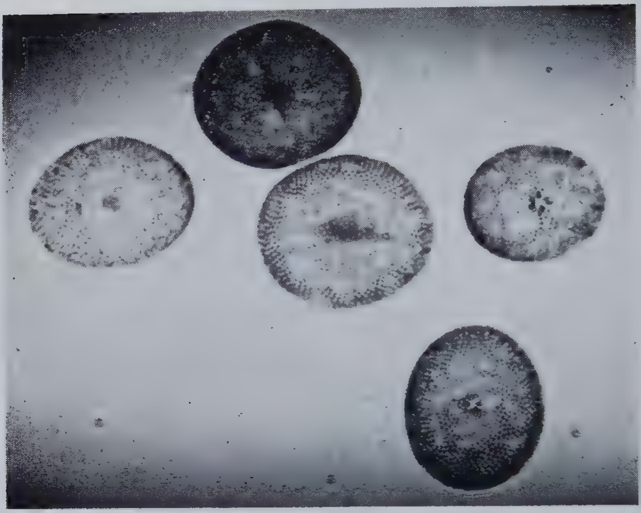

FIG. 1.—Group of sterrasters showing the greatest and intermediate dimensions; magnified approximateley 115×.

0·30 mm, and the intermediate dimension from 0·10 mm to 0·20 mm. The most common values are 0·17 to 0·20 mm by 0·12 to 0·14 mm for greatest and intermediate dimensions respectively. The ratio of the intermediate to the greatest dimension ranges from 2:3 to 5:6, in general being nearer the lower value for the larger specimens. The ratio of the least to the greatest dimension is commonly just over 1:2.

A few individuals still consist of unaltered opaline silica. These are translucent in direct illumination and are isotropic when viewed in oils under crossed nicols. Most specimens, however, are slightly altered and, except for any superficial stains, appear white in direct light. Immersed in oils they transmit light well enough to show only surface features, although under crossed nicols they remain rather dark.

Structurally the sterrasters consist of a large number of very fine rods or rays of silica radially arranged which, in the unaltered specimens, form a solid mass. In optical section, at the centre of the sclerite an irregular group of minute granules is seen radially arranged parallel to the proximal ends of the rays. The distal ends of the rays project beyond the solid body of the sterraster and are more or less evenly distributed over the surface giving it a knobbed or granulose appearance. Viewed end-on the rays appear nearly circular to polygonal. In well preserved specimens under high power, the distal ends are seen to be equipped with a verticil of short conical spines distributed somewhat

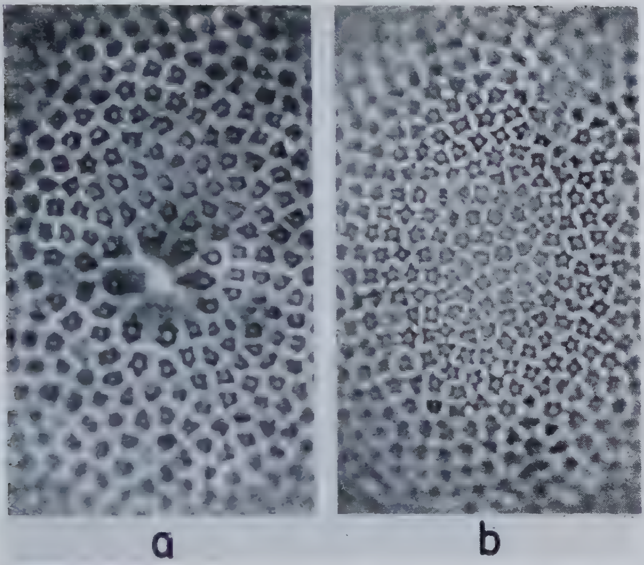

FIG. 2.—Surface view of sterrasters: (a) showing the umbilicus; magnified approximately 600×; (b) side opposite the umbilicus showing verticils of spines on the ends of the rays; magnified approximately 500×.

irregularly about the ray and perpendicular to its axis (Fig. 2). Generally six and, less commonly, five such spines are observed though greater and lesser numbers of spines occur. Where the sterrasters have been subject to wear, in some instances the protruding distal ends of the rays apparently have been broken off leaving certain areas of the surface free of them. In other cases the verticil of spines has been lost leaving the ray ends rather rounded.

Although many of the slightly altered specimens are completely solid, a portion of the interior of some individuals appears to have been dissolved. This is shown by several broken specimens which have a thin open layer between a centrally disposed spherical body and a thick outer wall of radially arranged rays. The structure of the sterrasters is thus concentric as well as radial. The central body, supported in position by some of the rays which extend across the open layer, seems to correspond to the internal "growth-zone" of sterrasters of *Geodinella* figured by Lendenfeld (1910, p. 216; plate 3, figs 7 and 9) who describes these spicules as "paratangentially stratified".

The inference that some sterrasters have been partially dissolved is supported by the fact that numerous broken megasclere spicules in the same preparations exhibit corroded axial canals which are considerably enlarged. The enlargement presumably is due to solution since, in many instances, the spicules are otherwise unaltered, retaining a clear glassy appearance. The corroded canals not uncommonly are partially infilled with a finely divided white mineral substance. Hinde and Holmes (1892) attribute to partial solution the enlargement of axial canals of both fossil spicules and detached spicules of recent forms dredged from the present sea bottom. Hinde (1887, pp. 54-58) has discussed in detail the alteration and dissolution of siliceous spicules during fossilization. Inasmuch as apparently only broken megascleres in the preparations examined have corroded canals, it seems probable that likewise only sterrasters in which fractures were formed during fossilization have suffered partial solution.

IDENTIFICATION

The sterrasters described above are typical of those found in sponges of the family Geodiidae Gray, 1867, order Choristida Sollas, 1888, of which the type genus is *Geodia* Lamarck, 1815. In the living animal densely packed sterrasters form a dermal armour in the cortex, but upon the death and subsequent disintegration of the sponge the sterrasters, together with the other spicules, are widely scattered so that only detached skeletal elements occur in microfaunal preparations.

Among the megascleres associated with the sterrasters, dichotriaenes and large oxeas are most common, but several other types of triaenes and even lithistid and hexactine spicules are also present. These serve to show that skeletal elements of many types of sponges have been intimately intermingled during deposition. Such intermingling is typical of deposits of detached spicules and is to be expected here in view of Dendy's (1924, p. 270) remarks on the "astonishing richness" and variety of the modern sponge fauna of New Zealand. De Laubenfels (1955, p. E28) has pointed out that, "it is rarely possible to identify a sponge genus, family, or order from the evidence of isolated spicules." On the other hand, the distinctive structure of the sterrasters allows them to be confidently assigned to the family Geodiidae. Prof. de Laubenfels has informed the writer (pers. comm.) that the genus *Geodia* is certainly represented but the possible presence of other genera of the Geodiidae cannot be excluded. Variation in size and detail of the sterrasters, plus the evidence for intermingling of spicules, support this conclusion.

Modern Geodiidae reported from New Zealand seas include *Geodia regina* Dendy, *G. rex* Dendy, and *Geodinella vestigifera* Dendy (Dendy, 1924; Bronsted, 1924, 1926). Also Lendenfeld (1910) has described *Geodia lophotriaena* from specimens presumed to have been taken from New Zealand waters. Among these forms dimensions given for sterrasters of *Geodia regina* (·187 × ·153 mm) and *Geodinella vestigifera* (·14 × ·12 mm) lie within the range observed for the specimens from western Wellington, while sterrasters of *Geodia rex* (·48 × ·40 mm) are considerably larger and those of *G. lophotriaena* (·03 — ·045 × ·03 — ·044 mm) are much smaller and more nearly circular in outline.

Members of the Geodiidae are known to range ás fossils back to the lower Carboniferous (Hinde, 1888). They are especially abundant in the Cretaceous of Britain and Germany but only a single genus has been reported previously from New Zealand. Hinde and Holmes (1892, pp. 233-236) described two forms (*a* and *b*) of *Geodites* Carter on the basis of detached megasclere spicules from a siliceous bed which directly underlies the Ototara Limestone (Upper Eocene) near Oamaru, Otago. As noted by Hinde (1888), no formal definition of the genus *Geodites* was given by its author. Carter (1871) simply selected from a deposit of detached spicules characteristic megascleres to make up a "spicular combination" like that of the existing genus *Geodia*. The largest sterrasters present in the deposit were arbitrarily chosen to complete the combination which Carter (1871, p. 134) considered "conventional and provisional". Sterrasters from the deposit of detached spicules at Oamaru were also assigned to *Geodites* but Hinde and Holmes (1892, p. 235) noted that, ". . . they show the same structural details as the [sterrasters] of recent species of *Geodia*."

The sterrasters described herein are similar to those reported by Hinde and Holmes and may represent the same genus or genera. However, there is no justification for assigning the present examples to the genus *Geodites* in view of the arbitrary and "provisional" nature of the original description by Carter and more especially since *Geodites* has recently been restricted in definition on the basis of megasclere spicules by de Laubenfels (1955, p. E42). Further, the late Cenozoic age of the enclosing sediments suggests that the sterrasters here reported should bear closer affinities to existing forms than to the early Cenozoic examples from Oamaru.

SIGNIFICANCE

Geodine sterrasters are distinctive, siliceous skeletal elements of marine sponges and, together with other spicule types, they have proved useful to the writer in determining the marine origin of sediments in which other definitive criteria are lacking. For example, beds of the Hawera Series in the vicinity of Palmerston North, considered by some workers (Turner, 1944) to be non-marine, contain abundant sterrasters and other sponge spicules. In this investigation the siliceous nature of the spicules was particularly helpful since any calcareous microfaunal evidence that may have been present has been removed by leaching. It is possible that, being minute, small numbers of sterrasters and other spicules might be transported short distances from their original marine environment to a non-marine site of deposition, either by tidal currents flowing up estuaries or by wind blowing landward across exposed intertidal sediments. However, where present in abundance they may, in the absence of compelling evidence to the contrary, be regarded as a trustworthy indication of a marine (or possibly estuarine) origin of the enclosing sediments.

In view of the facts that geodine sponges are now living in New Zealand waters, that their remains have been identified from both late and early Cenozoic beds, and that the family ranges back to the Carboniferous, it may be anticipated that their distinctive sterrasters will be found in appropriate sediments throughout the Upper Cretaceous and Cenozoic "covering strata" of New Zealand.

ACKOWLEDGEMENTS

The writer is indebted to Professor M. W. de Laubenfels who kindly read the manuscript and offered valuable suggestions. Helpful discussions with Dr M. T. Te Punga, Dr H. B. Fell, and Professor H. B. Whittington are also acknowledged. The geological work which led to paper was aided by a New Zealand University Research Grant.

REFERENCES

BRONSTED, H. V., 1924: Sponges from New Zealand. Part I. *Vidensk. Medd. dansk naturh. Foren. Kbh., 77* : 435-83.

———, 1926: Sponges from New Zealand. Part II. *Vidensk. Medd. dansk naturh. Foren. Kbh., 81* : 295-331.

CARTER, H. J., 1871: On Fossil Sponge-spicules of the Greensand Compared with those of Existing Species. *Ann. Mag. nat. Hist., 4th ser., 7* : 112-41.

DENDY, A., 1924: Porifera. Part I. Non-Antarctic Sponges. *Nat. Hist. Rep. Terra Nova Exped. Zool., 6 (3)* : 269-392.

HINDE, G. J., 1887-1912: "A Monograph of the British Fossil Sponges". Vol. I. Palaeontographical Society, London.

HINDE, G. J.; HOLMES, W. M., 1892: On the Sponge-remains in the Lower Tertiary Strata near Oamaru, Otago, New Zealand. *J Linn. Soc. (Zool.), 24* : 177-262.

LAUBENFELS, M. W. DE, 1955: "Porifera" *in* "Treatise on Invertebrate Paleotology". Part E. Geological Society of America, New York, pp. E21-E112.

LENDENFELD, R. VON, 1910: The Sponges. 1. The Geodiidae. *Mus. comp. Zool., Harv., Mem. 41 (1).*

TE PUNGA, M. T., 1954: Fossiliferous Late-Pleistocene Beds in a Well at Awahuri, near Palmerston North. *N.Z. J. Sci. Tech., B36 (1)* : 82-92.

TURNER, R. H., 1944: "Geology of Northern Wellington and Southern Hawke's Bay". Unpublished report lodged in Victoria University Library, Wellington.

THE OCCURRENCE OF ARATAURAN BEDS SOUTH OF NUGGET POINT, SOUTH OTAGO, NEW ZEALAND

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(Received for publication, 23 July 1958)

Summary

The upper part of the Otapirian Stage and the Arataurian Stage are recognized in the sequence south of Nugget Point, and the position of the Triassic-Jurassic boundary fixed. The Otapirian Stage is 690 ft thick and Aratauran 1,880 ft.

Introduction

Through the efforts of many workers the Triassic sequence from Nugget Point southwards to the south side of Roaring Bay has become well known. Mackie (1935, p. 276) lists the observers during the period between the first examination by Lindsay (1862, p. 30) in 1860-61 and the date of his publication. Later, in 1955, Campbell (pp. 1,039-41) showed the Oretian Stage at Nugget Point to be 1,500 ft thick and to include beds 14 and 15 of Mackie (1935, p. 280), thus confirming Marwick's (1953, p. 14) conclusion. The Otapirian Stage was described by Campbell (pp. 47-8) in 1956, when he concluded that "a basal Otapirian faunule assemblage is preserved in the beds at the south end of Roaring Bay".

Although several workers, notably McKay (1877) in 1873, Park (1904), and Mackie (1935), had examined the sequence southward from Roaring Bay to the Catlins River mouth, no information had been obtained about the sequence between the basal Otapirian beds at the south side of Roaring Bay and the Ururoan beds with *Pseudaucella marshalli* (Trechmann) on the north side of Sandy Bay (Figs 1 and 2), because of the rugged nature of this part of the coastline. The coast between Roaring Bay and the mouth of the first creek to the south is divided into three shallow embayments by narrow points, impassable at sea-level. These are lettered A, B, and C in Figs 1 and 2.

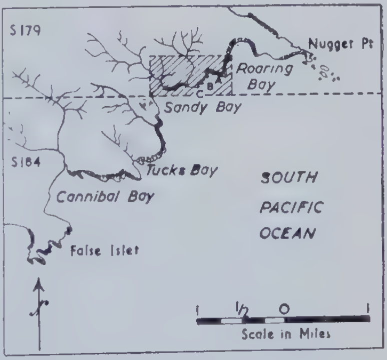

Fig. 1.—Map of Nugget Point—False Islet coastal section. Area discussed indicated by diagonal hatching. Impassable points lettered A, B, and C.

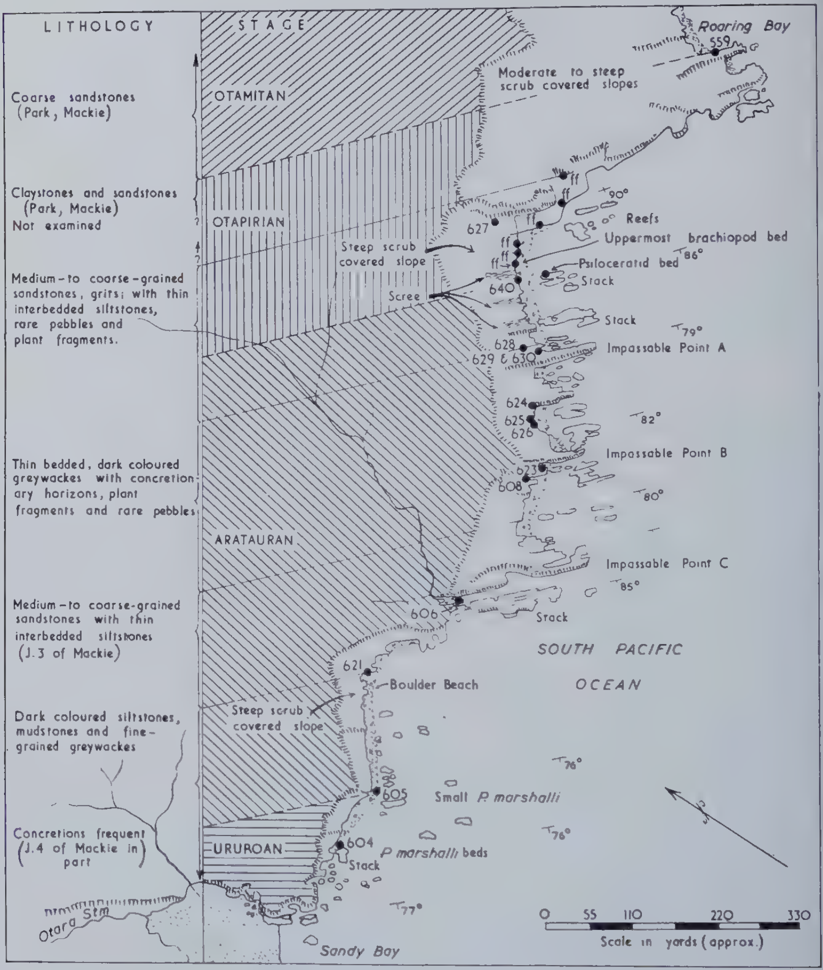
LITHOLOGY
STAGE
Coarse sandstones (Park, Mackie)
OTAMITAN
Claystones and sandstones (Park, Mackie) Not examined
OTAPIRIAN
Medium-to coarse-grained sandstones, grits; with thin interbedded siltstones, rare pebbles and plant fragments.
Thin bedded, dark coloured greywackes with concretionary horizons, plant fragments and rare pebbles
ARATAURAN
Medium-to coarse-grained sandstones with thin interbedded siltstones (J.3 of Mackie)
Dark coloured siltstones, mudstones and fine-grained greywackes
Concretions frequent (J.4 of Mackie in part)
URUROAN
Otara Stm
Roaring Bay
559
Moderate to steep scrub covered slopes
ff
90°
627
Reefs
Uppermost brachiopod bed
86°
Steep scrub covered slope
Psiloceratid bed
Stack
640
Scree
Stack
79°
628
629 & 630
Impassable Point A
624
625
626
82°
Impassable Point B
623
608
80°
Impassable Point C
85°
606
Stack
SOUTH PACIFIC OCEAN
621
Boulder Beach
Steep scrub covered slope
76°
605
Small P. marshalli
76°
604
P. marshalli beds
Stack
77°
Sandy Bay
0 55 110 220 330
Scale in yards (approx.)

FIG. 2.—Stratigraphy of the sequence between the south side of Roaring Bay and north side of Sandy Bay. Fossil localities indicated by fossil record form numbers (e.g., 604) for S179 and by ff. Figure based on magnification (× 4) of aerial photograph and field drawings.

The authors examined the section on 16 September 1957, and this paper includes the results of the exploratory visit. Thicknesses are based on measurements from aerial photographs and on the angle of dip.

STRATIGRAPHY

Details of the sequence, the lithology, structure and fossil occurrences, in the first embayment south of Roaring Bay are given in Figs 2 and 3.

Clavigera bisulcata Hector and *Spiriferina* (*Rastelligera*) sp. are present in the coarse-grained sandstone bed forming the cliff face at the northern end of the embayment. The overlying 640 ft of sediments, coarse grits, sandstones and siltstones, locally pebbly and with carbonized plant fragments, are well exposed in strike reefs extending out to sea and in the face at the inland edge of the boulder beach. Beds with brachiopods and lamellibranchs (Figs 2 and 3, indicated by ff) were noted at horizons 300, 400, 480, 530, and 610 ft, and crinoid stems at 560 ft above the base of the Otapirian Stage (S179/559). For example, a coarse-grained sandstone bed (S179/627), forming a very prominent cliff in the scrub at the north end of the embayment, 400 ft above the base of Mackie's (1935, p. 280) bed "t", contains *Clavigera bisulcata*, "*Myophoria*" sp., "*Rhynchonella*" sp. and *Spiriferina* sp. Approximately 75 yards south of S179/627 and 6 yards north of a prominent scree (Fig. 2) which masks the sequence for the overlying 50 ft, is the uppermost bed in which Otapirian brachiopods were found.

South of the scree and continuing to approximately 20 yards north of the first impassable point (A), the section consists of coarse grits and sandstones with minor interbedded siltstones, obscured by scree in two more places. In this section, 690 ft above the base of the Otapirian Stage (80 ft above the highest Otapirian bed), Mr J. D. Campbell and Professor D. S. Coombs later discovered psiloceratid ammonites associated with *Otapiria marshalli* (Trechmann) in a siltstone bed (S179/640) on the north side of a large stack and in the cliff at the back of the boulder beach. Two hundred and fifty feet stratigraphically above the psiloceratid bed, the lithology changes to thin-bedded, finer-grained, dark grey greywackes and siltstones. A specimen of *Otapiria marshalli* was collected from a dark, blue-grey, fine-grained greywacke bed (S179/628), 27 ft above the change in lithology, and 12 ft above S179/628 an ammonite fragment was found in a thin bed of medium-grained sandstone (S179/630). After an unfossiliferous gap of six feet *Chlamys* sp. and *Plicatula* sp. were collected from a 16 inch, coarse pebbly grit containing numerous shell fragments (S179/629).

A sequence (Figs 2 and 3) of about 700 ft of dark coloured greywackes and siltstones continues to 100 yards north of the creek immediately south of an impassable point (C) (Fig. 2), the upper boundary corresponding with the top of Mackie's (1935, p. 283) bed J.2. The sequence is notable for the presence of horizons of calcite-cemented concretions, large carbonized plant stems and pinules in many beds, rare pebbles, for minor calcite-zeolite veining, slickensiding of

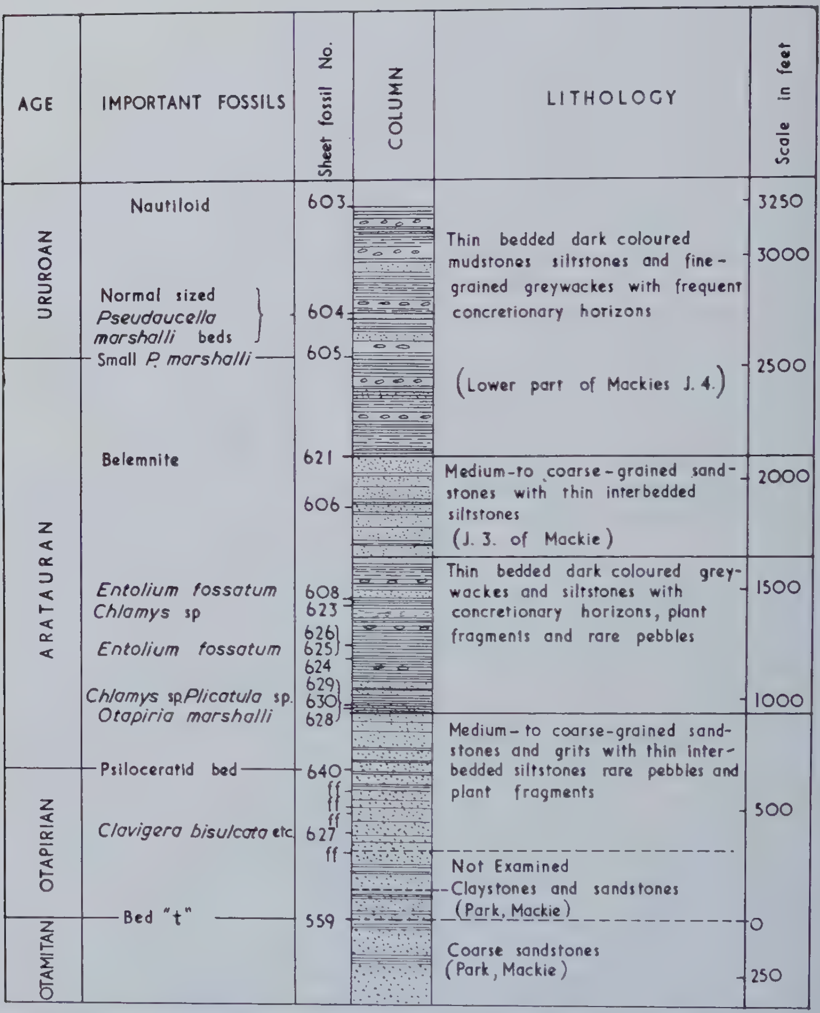
AGE
IMPORTANT FOSSILS
Sheet fossil No.
COLUMN
LITHOLOGY
Scale in feet
URUROAN
ARATAURAN
OTAPIRIAN
OTAMITAN
Nautiloid
Normal sized Pseudaucella marshalli beds
Small P. marshalli
Belemnite
Entolium fossatum
Chlamys sp
Entolium fossatum
Chlamys sp. Plicatula sp.
Otapiria marshalli
Psiloceratid bed
Clavigera bisulcata etc.
Bed "t"
603
604
605
621
606
608
623
626
625
624
629
630
628
640
ff
ff
ff
627
ff
559
Thin bedded dark coloured mudstones siltstones and fine-grained greywackes with frequent concretionary horizons
(Lower part of Mackies J. 4.)
Medium-to coarse-grained sandstones with thin interbedded siltstones
(J. 3. of Mackie)
Thin bedded dark coloured greywackes and siltstones with concretionary horizons, plant fragments and rare pebbles
Medium-to coarse-grained sandstones and grits with thin interbedded siltstones rare pebbles and plant fragments
Not Examined
Claystones and sandstones
(Park, Mackie)
Coarse sandstones
(Park, Mackie)
3250
3000
2500
2000
1500
1000
500
0
250

FIG. 3.—Stratigraphical column of sequence between Roaring Bay and Sandy Bay. Fossil localities indicated by fossil record form numbers (e.g., 640) for S179 and by ff.

bedding surfaces and small faults. Fossils occur very sporadically in this sequence.

The stratigraphical position and faunules of fossiliferous beds above the psiloceratid bed (S179/640) are as follows: S179/624, 500 ft (indeterminable brachiopod); S179/625, 550 ft (*Entolium fossatum* Marwick, "*Rhynchonella*" sp., ? juvenile *Otapiria*); S179/626, 569 ft (indeterminable fragment of gastropod); S179/623, 740 ft (*Chlamys* sp.); S179/608, 770 ft (*Entolium fossatum* Marwick, ? *Pseudaucella* sp., Pteriid cf. *Otapiria*).

The overlying 450 ft of strata, equivalent to Bed J.3 of Mackie (1935, p. 283), are mostly light blue-grey, coarse-to-medium grained sandstones, sometimes concretionary and with occasional pebbles and plant fragments. A vertical bed (S179/606) in a cove five chains north of Sandy Bay and forming the northern margin of a creek, contains a characteristic gryphaeoid pteriid, possibly a new genus. Its horizon is 1,190 ft above the psiloceratid bed. The uppermost three inches of the pebbly sandstone bed (S179/621) at the top of J.3 contains indefinite fossil-like impressions, but only a small, poorly preserved belemnite was collected. Between the last two fossiliferous localities and in line with the axis of flow of the creek (Fig. 2), the sequence is badly shattered, and includes several almost vertical zones of calcite-zeolite cemented rock up to 3 ft thick. No displacement has been detected along these zones.

Above the sandstones is a sequence (Figs 2 and 3) of thin-bedded, dark blue-grey mudstones, siltstones, and fine-grained greywackes, commonly with concretionary horizons. This is Bed J.4 of Mackie (1935). Small *Pseudaucella marshalli* appear in dark blue-grey siltstone (S179/605) 480 ft above the base of J.4 and 1,880 ft above the incoming of *Otapiria marshalli*. The small *P. marshalli* are present in several beds up to 650 ft above S179/621, when shell beds of normal-sized *P. marshalli* appear. The overlying 35 ft of sediments (S179/604) are composed of numerous shell-beds of *P. marshalli*, not exceeding 10 inches in thickness and separated by barren bands. Except for a nautiloid found on the upper surface of a thin stratum of siltstone (S179/603), 450 ft above the uppermost *P. marshalli* bed, the rest of Mackie's J.4 is unfossiliferous.

DISCUSSION

Until the lower Jurassic sequences in New Zealand have been adequately studied, the upper and lower boundaries of the lowest Jurassic Stage, the Aratauran, can be only tentatively defined. Campbell (1956, p. 699), following Marwick (1953, p. 21), places the upper boundary of the Upper Triassic Otapirian Stage, in the type section in the Otapiri Valley, below "the appearance of a fauna including psiloceratid ammonites". Providing no typical Aratauran assemblage appears at a lower horizon than psiloceratid ammonites, the ammonites are an excellent indicator for the commencement of the stage.

In the Roaring Bay—Sandy Bay section the lowest Aratauran is the psiloceratid ammonite bed found by Professor D. S. Coombs and Mr J. D. Campbell, 280 ft below the *Otapiria marshalli* bed (S179/628) discovered by the authors. The Aratauran stage in this section is considered to include the sediments from the psiloceratid bed to the lowest stratum containing small specimens (S179/605) of *Pseudaucella marshalli.* Thus the Otapirian Stage is 690 ft thick, and the Aratauran 1,880 ft thick.

ACKOWLEDGEMENTS

The authors are grateful to Professor D. S. Coombs and Mr J. D. Campbell for permission to publish their discovery of psiloceratid ammonites, and for valuable comments on the manuscript.

REFERENCES

CAMPBELL, J. D., 1955: The Oretian Stage of the New Zealand Triassic System. *Trans. roy. Soc. N.Z. 82 (5)* : 1,033-47.

———, 1956: The Otapirian Stage of the Triassic System of New Zealand. Part II. *Trans. roy. Soc. N.Z. 84 (1)* : 45-50, 1 text-fig.

LINDSAY, W. L., 1862: "The Place and Power of Natural History in Colonization with Special Reference to Otago". Published as a pamphlet, Dunedin, January 1862. (Not seen.)

MACKIE, J. B., 1935: The Geology of the Glenomaru Survey District, Otago, New Zealand. *Trans. roy. Soc. N.Z. 64 (3)* : 275-302, Pls. 51, 51a.

MARWICK, J., 1953: Divisions and Faunas of the Hokonui System (Triassic and Jurassic). *N.Z. geol. Surv. pal. Bull. 21,* 141 pp., 17 Pls.

McKAY, A., 1877: Reports Relative to Collections of Fossils in the South-East District of the Province of Otago. *N.Z. geol. Surv. Rep. geol. Explor. 1873-4, 8B* : 59-73

PARK, J., 1904: On the Subdivisions of the Lower Jurassic Rocks of New Zealand. *Trans. N.Z. Inst. 36* : 373-404, Pls. xxviii-xxxi.

NEW ZEALAND FORAMINIFERA: KEY SPECIES IN STRATIGRAPHY—No. 6

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Summary

The following Foraminifera are of stratigraphic importance in New Zealand and especially in the Waipara district: *Pseudoclavulina anglica* Cushman (Teurian); ***Sigmoilopsis neocelata*** n.sp. (Duntroonian? Waitakian to Altonian); ***S. compressa*** n.sp. (Awamoan and Altonian); ***Buliminella waiparaensis*** n.sp. (Haumurian and Teurian); ***Bolivina fyfei*** n.sp. (Kapitean to Nukumaruan); ***Loxostomum pakaurangiensis*** n.sp. (Awamoan to Waiauan); ***Notorotalia wilsoni*** n.sp. (Altonian to Waiauan); ***Notorotalia aranea*** n.sp. (Otaian? Hutchinsonian and Awamoan); *Globigerina pseudoiota* Hornibrook (Waipawan and Mangaorapan); *G. gravelli* Bronniman (Waipawan); *G. soldadoensis* Bronniman (Waipawan); ***Globorotalia zealandica*** n.sp. (Awamoan and Altonian); ***Cibicides thiaracuta*** n.sp. (Altonian to Tongaporutuan).

INTRODUCTION

The title adopted for this paper continues, after a lapse of eleven years, the well-known series of five New Zealand "Key Species" papers published from 1939 to 1947 by the late H. J. Finlay while micropaleontologist for the New Zealand Geological Survey.

Finlay's Key Species papers, although unduly brief and sketchy in their coverage of New Zealand Cretaceous and Tertiary Foraminifera, have been of immense value in providing the basis for the currently used time-stratigraphic divisions in this country in so far as these are based on microfossils. They are not, however, a substitute for much needed monographic, fully illustrated descriptions of foraminiferal faunas from important sections which Finlay never had time to attempt. The present paper has been made necessary mainly because of the need for names for a number of undescribed, stratigraphically important Foraminifera collected by various geologists in the Waipara district, North Canterbury. A New Zealand Geological Survey Bulletin covering the area is at present in preparation under the authorship of D. D. Wilson (formerly of New Zealand Geological Survey).

Types of all the species described as new in this paper and other figured specimens are deposited in the collections of the New Zealand Geological Survey, Lower Hutt, New Zealand. Primary types are catalogued under the prefix **TF** and figured specimens not having primary type status are catalogued under the prefix **FP**. As far as possible, paratypes, topotypes or other identified specimens will be sent to the U.S. National Museum, Washington, and the National Museum of Victoria, Melbourne, Australia. A similar undertaking was given by Finlay in the first Key Species paper (1939a, p. 505) but partly because of the

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Second World War and partly because of pressure of work, Finlay never managed to fully carry out his intentions. The necessity of having the New Zealand microfauna represented in overseas collections, available for study, does not have to be emphasised. Finlay's promise will be fulfilled as soon as possible and the N.Z. Geological Survey policy of depositing specimens in the above mentioned institutions will be continued.

Localities quoted in the present paper bear either a New Zealand Fossil Record Number (e.g., S68/781) or a serial New Zealand Geological Survey foraminiferal collection number prefixed by the letter **F**, or both. Numbers prefixed by **GS** refer to the New Zealand Geological Survey macrofossil collections. Wherever possible, grid coordinates in terms of the New Zealand 1-Mile Map Series (N.Z.M.S. 1) are given.

All figures were drawn by the writer with the aid of a camera lucida.

SYSTEMATICS

Pseudoclavulina anglica Cushman, Figs 1–2.

1886 *Clavulina communis* Sherborn and Chapman (not of d'Orbigny); J. R. micr. Soc., Ser 2, 6 : 743, pl. 15, fig. 1.

1936 *Pseudoclavulina anglica* Cushman; Spec. Publ. Cushman Lab. No. 6, p. 18, pl. 3, fig. 5.

1940 *Pseudoclavulina* cf. *anglica* Cushman; Finlay and Marwick, Trans. roy. Soc. N.Z., 70 (1) : 106.

1957 *Pseudoclavulina* aff. *anglica* Cushman; Hornibrook and Harrington, N.Z. J. Sci. Tech. B38 (6) : 665, fig. 6, 666-8.

DESCRIPTION: Initial triserial portion small and very distinctly triangular, followed abruptly by a rectilinear series of up to 10 globose chambers, initially somewhat compressed and sometimes angular, but becoming progressively more separated and constricted. The test material consists of moderately coarse sand grains of even size. Aperture terminal, situated in a slight prominence, the sides projecting inwards irregularly giving a lobed appearance.

DIMENSIONS OF FIGURED SPECIMEN, FP1101: length, 2·69 mm; diameter of final chamber 0·62 mm.

VARIABILITY: The overall size is subject to considerable variation from one locality to another, the individuals in the sample containing the figured specimen being the largest encountered. The angularity of the triserial portion is sometimes continued in the first two or three rectilinear chambers.

N.Z. GEOLOGICAL SURVEY CATALOGUE NOS OF FIGURED SPECIMENS: FP1101, 1102.

LOCALITY AND AGE OF FIGURED SPECIMENS: F5934, main road, north of the bridge across the Waipawa River, Hawke's Bay, N.Z.M.S. 1, Sheet N141 (Provisional edit., 1943), grid ref. 004847; blue-grey siltstone below the Waipawa black siltstone. Teurian Stage (Danian-Paleocene).

REMARKS: The close resemblance of the New Zealand form to *P. anglica* described by Cushman from the Eocene London Clay leaves little grounds for regarding it as a separate species. The wide distribution during Danian, Paleocene, and Eocene time of forms very similar to *P. anglica*, some of which may be identical with that species, is an additional reason for not proposing a new specific name for the New Zealand one.

DISTRIBUTION: Within New Zealand, *Pseudoclavulina anglica* occurs in the uppermost part of the Mata Series. It is common in the Teurian of Hawke's Bay including the black siltstone facies at Waipawa and it is in the type Teurian. In North Canterbury *P. anglica* has been found in the top foot of the Waipara Greensand at the mouth of Birch Stream (S68 774, F11272). The southernmost record is in the Moeraki Formation (F5746) at Hampden Beach. In Northland, in the Tangowahine Valley, this species occurs in brown mudstone, with a microfauna similar to the Waipawa black siltstone, overlain by Dannevirke Series.

Only in Hawke's Bay have rocks containing *P. anglica* been dated definitely as Teurian by Foraminifera. The upper member of the Waipara Greensand, although dated by the microflora as Teurian (Dr R. A. Couper, pers. comm.) does not contain an adequate foraminiferal fauna. If *P. anglica* is confined to the Teurian, as appears likely, its presence is the first positive foraminiferal evidence for the Teurian age of the Moeraki Formation. (A Teurian age for the Moeraki beds is supported by both microflora and hystrichospherids (Dr R. A. Couper, pers. comm.)).

According to Cushman (1937, p. 114), *Pseudoclavulina anglica* has a wide distribution; he comments as follows: "Probably Heron-Allen and Earland's record for *Clavulina parisiensis* from the London clay (*Journ. Roy. Micro. Soc.* 1908, p. 332) is *anglica*; also Franke's *C. parisiensis* from the lower Eocene of Schwarzenback, Germany (*Jahrb. Kon. Preuss. Geol. Landes., vol. 32*, pt. 2, 1911, p. 108 (list) may be this species, and his figure from the Paleocene (*Danmarks Geol. Unders., vol. 2*, No. 46, 1927, p. 10, pl. 1, fig. 6) may be the same".

Pseudoclavulina anglica was recorded from the Swedish Upper Danian and Paleocene and from the Paleocene of Denmark, Germany, and Holland by Brotzen (1948, p. 37, 38, pl. 5, figs 1, 2) who noted that his specimens differed little from specimens from the English Eocene. In his synonymy for this species, Brotzen included the record of *Clavulina parisiensis* by Glaessner (1937b, p. 353) from lower Tertiary of the Caucasus.

The occurrence in the Danian, Paleocene, and lower Eocene in many parts of the world, of the following Pseudoclavulinas, very similar to *anglica,* seems to have significance:

> *Clavulinoides algeriana* ten Dam and Sigal, 1950, Dano-Montian of Eastern Algeria.
> *Clavulinoides aspera* (Cushman) var. *whitei* (Cushman and Jarvis), Danian-Paleocene, Lizard Springs, Trinidad.
> *Pseudoclavulina copiosa* Israelsky, 1951, Upper Paleocene or Lower Eocene, Lodo Formation, California.
> *Pseudoclavulina emaciata* Israelsky, 1951, Upper Paleocene or Lower Eocene, Lodo Formation, California.

All these species have in common the distinct but small initial triserial distinctly triangular portion, a very similar overall shape and size, and regular grain size in the test walls, and together form a group of closely related forms, some of which may be identical with *P. anglica*.

KNOWN RANGE IN NEW ZEALAND: Teurian Stage (Danian-Paleocene).

Sigmoilopsis neocelata Hornibrook, **n.sp.,** Figs 3, 4, 10.

DESCRIPTION: Test roughly quinqueloculine in chamber arrangement, sharp-angled with pinched in chambers, their outer edges projecting very distinctly from the body of the shell in well developed specimens. Aperture, in unbroken specimens, an elongate opening with a small central tooth situated at the end of a short neck. Exterior of test covered with fine sand grains. In thin section the test is seen to be secondarily arenaceous, the inner walls of the chambers being calcareous.

DIMENSIONS OF HOLOTYPE: length, 1·23 mm;
greatest diameter, 0·58 mm.

VARIABILITY: The sharpness of the test angles and prominence of the individual chambers are subject to variation, some specimens being more inflated than others.

TYPES: New Zealand Geological Survey Catalogue No. TF1325; holotype and 7 paratypes.

TYPE LOCALITY: S31/502, F6230, Fletcher Creek, Reefton, 117 ch upstream from the junction with Coll Creek, N.Z.M.S. 1 Sheet S31 (Provisional edit., 1944), grid ref. 291444; calcareous mudstone associated with limestone. Collected by Dr M. Gage.

TYPE LEVEL: Otaian Stage (Upper Oligocene).

REMARKS: Distinguished from other New Zealand *Sigmoilopsis* by the sharply angled test with distinctly separated chambers. This species has previously been referred to in reports and faunal lists as *Sigmoilopsis* cf. *celata* (Costa).

DISTRIBUTION: Frequent in the Grey Marl in North Canterbury (Otaian). Common in the upper part of the Weber formation (Waitakian) on the east coast of the North Island. The earliest known occurrence of *S. neocelata* is from the type Weber formation near Weber township (Hawke's Bay) in a microfauna (F5982) that is possibly as old as Duntroonian (*Uvigerina maynei* Chapman, *Globigerina angipora* Stache). It is common in the basal Blue Bottom (Waitakian) at Runanga and in other Waitakian and Otaian microfaunas from the West Coast of the South Island. The highest known occurrences of *S. neocelata* are in Altonian mudstone (F5979), east of Tumumu, Hawke's Bay, and in the basal Blue Bottom (F5713, Altonian) in Tansey Creek, Westland.

KNOWN RANGE: Duntroonian? Waitakian to Altonian (Lower Oligocene?, Mid Oligocene to Lower Miocene).

Sigmoilopsis compressa Hornibrook, **n.sp.,** Figs 5, 6, 11.

DESCRIPTION: Test relatively smooth and depressed without angles and showing little sign of chambering externally. The sides are gently convex and the periphery evenly rounded. Aperture situated in a short tubular neck, divided by a central simple tooth. Seen in thin section, the initial whorl is sigmoiline but later chambers are added alternately on either side in a single plane as in *Spiroloculina*. The thick, outer part of the test wall is secondarily arenaceous, built of small, even-sized grains, the thin, inner portion of the walls being calcareous.

DIMENSIONS OF HOLOTYPE: length, 0·79 mm;
breadth, 0·55 mm;
thickness, 0·29 mm.

VARIABILITY: Fairly constant except for variation in the degree of flattening of the test.

TYPES: New Zealand Geological Survey Catalogue No. TF1326; holotype and 25 paratypes.

TYPE LOCALITY: N68/650, F8276, N.Z.M.S. 1 Sheet S68 (edit., 1950), grid ref. 218101. Northern tributary of Dovedale Stream rising near Totara Trig., highly calcareous siltstone, 500 ft above the top of the Weka Pass Limestone. Collected by Mr D. D. Wilson, 1953.

TYPE LEVEL: Awamoan Stage (Upper Oligocene or Lower Miocene).

REMARKS: In assigning this species to *Sigmoilopsis* the writer interprets the genus broadly, including forms that abandon a sigmoiline chamber arrangement after the first whorl and thereafter add chambers in a single plane. Judging from the type figure, *Sigmoilina latissima Chapman*, 1941, appears to fall within the latter category. Distinguished from other New Zealand *Sigmoilopsis* by the flattened, compressed test. The small, even sand grains in the exterior of the test wall distinguish *S. compressa* from the rather similar *S. wanganuiensis* Vella, in the Wanganui Series.

DISTRIBUTION: Common in the Awamoan and Altonian siltstone in the Dovedale district and in the lower part of the Ihungia formation (Altonian) on the east coast of the North Island. *Sigmoilopsis compressa* occurs also in Southland mudstones, probably of Altonian age, in Monowai and Lillburn Survey Districts. On the West Coast of the

South Island it occurs in the basal Blue Bottom Formation (F5713, Altonian) in Tansey Creek. It also occurs in Mokau sandstone (Altonian) in North Taranaki.

KNOWN RANGE: Awamoan to Altonian (Upper Oligocene? to Lower Miocene).

Buliminella waiparaensis Hornibrook, **n.sp.,** Figs 7–9.

DESCRIPION: Test small and squat, surfaces densely ornamented with coarse papillae The chambers increase very rapidly in size and are subspherical, separated by distinctly indented sutures. Above the small initial portion, the first two whorls each consist of 4 chambers but in some mature individuals a third whorl consisting of only 3 chambers is developed. The aperture is a large, round, arched opening, its lower border formed by the penultimate chamber.

DIMENSIONS OF HOLOTYPE: length, 0·26 mm;
greatest diameter, 0·19 mm.

TYPES: New Zealand Geological Survey Catalogue No. TF1327; holotype and 15 paratypes.

TYPE LOCALITY: S68/109, F5329, east branch of the Grey River, dark mudstone 200 ft below the Kaitara greensand; 750 ft below "Amuri" Limestone. Collected by Dr B. W. Mason.

TYPE LEVEL: Loburn Formation, Haumurian Stage (Maestrichtian).

REMARKS: The generic location of this species is somewhat doubtful. Although it undoubtedly belongs to the Buliminidae and is closely related to *Buliminella*, the inflated pustuled chambers and wide aperture set it apart from the more typical members of that genus.

DISTRIBUTION: Known only from the upper Cretaceous of North Canterbury where it occurs in the Loburn clay (Haumurian) in the east branch of the Grey River (S68/109, F5329), in Haumurian glauconitic mudstone in the south branch of the Waipara River (S68/45, F9556) and in the Sulphur Mudstone in the middle Waipara River section (S68/686, F9662).

KNOWN RANGE: Haumurian to Teurian (Maestrichtian to Danian).

Bolivina fyfei Hornibrook, **n.sp.,** Figs 15, 16.

DESCRIPTION: A large, elongate *Bolivina* with up to 10 chambers on either side, regularly biserial throughout; surfaces smooth and glossy with dense fine pores. The initial chambers, which bear an apical spine, enlarge rapidly and become very inflated to form a smooth subcylindrical shell. Aperture an elongate, curved, rimmed opening in the terminal face, its lower border formed by the penultimate chamber.

DIMENSIONS OF HOLOTYPE: length, 0·74 mm;
breadth, 0·24 mm.

VARIABILITY: The tendency for most individuals to twist spirally about the axis of growth is quite marked but the degree of twisting varies from zero to nearly 90° in extreme cases and may be clockwise or anticlockwise.

TYPES: New Zealand Geological Survey Catalogue No. TF1328, holotype and 20 paratypes.

TYPE LOCALITY: F7030, N.Z.M.S. 1, Sheet S55 (Provisional edit., 1944), grid ref. 773762, opposite Glenstrae homestead, 300 yds S.E. from the Hundalee-Oaro road.

TYPE LEVEL: Hundalee Conglomerate, Waitotaran Stage (Pliocene).

REMARKS: Distinguished by the smooth, glossy, elongate, usually twisted, *Virgulina*-like shell with its apical spine. Named after Mr H. E. Fyfe who collected the sample.

DISTRIBUTION: Common in the Pliocene of North Canterbury, Marlborough, and Wairarapa, especially in the Waitotaran. The earliest known occurrence is in N165/552, F7785 (N.E. side of Palliser Bay, 130 ch. E. of end of road at Whangaimoana) in the Kapitean of the Palliser Bay section. These Kapitean specimens, however, are noticeably more compressed and squat than the Waitotaran ones. At least two occurrences can be recorded from the Nukumaruan: N165/587, F7589, fossiliferous sand immediately overlying lignite, 10 ch. downstream from Hautotara Bridge, Huangarua River; F5892 (AL 217) Mangaotoro N.W., S.D., 25 ch 195° from trig. 50.

KNOWN RANGE: Kapitean to Nukumaruan (Upper Miocene to Lower Pleistocene).

Loxostomum pakaurangiensis Hornibrook, **n.sp.,** Fig. 17.

DESCRIPTION: Test small, elongate, slightly twisted, excavated medially, sides subparallel, tapering very slightly towards the initial end, chambers increasingly inflated and more distinctly separated in the later half of the adult shell, up to 8 chambers on either side. Chambers in early half of shell are compact and regularly biserial and develop prominent ribs which run around the sides, turning upwards, and ending at the edge of the excavated median area that runs the whole length of the test. The later chambers become progressively overlapping and are coarsely porous, the ridges bordering the pores forming a hexagonal network. Aperture terminal, a large elongate opening, bordered by a thick rim.

DIMENSIONS OF HOLOTYPE: length, 0·62 mm;
breadth, 0·19 mm.

VARIABILITY: The initial half of the test is commonly more compressed than it is in the holotype. The ribs are suppressed and the initial half of the shell is smooth and translucent in a minority of specimens; in others the ribs and median trough are exaggerated.

TYPES: New Zealand Geological Survey Catalogue No. TF1329; holotype and 3 paratypes.

TYPE LOCALITY: F11414, GS1189, Pakaurangi Point, Kaipara Harbour, Hukatere Survey District. Collected by Dr H. J. Ferrar.

TYPE LEVEL: Altonian Stage (Lower Miocene).

REMARKS: Easily confused with species of *Virgulopsis* which approach *L. pakaurangiensis* very closely in size, shape, and ornament. Besides being biserial throughout, *L. pakaurangiensis* is distinguished from *Virgulopsis* by the broad distinct median trough.

DISTRIBUTION: *Loxostomum pakaurangiensis* is a very useful marker fossil appearing first in the Awamoan on the east coast of the South Island and being common thereafter in sandy lithology in the Southland Series.

In North Canterbury it appears in the Middle Waipara section in the yellow loose fine sands immediately below the Main Mt. Brown limestone. In the Weka Creek section it appears 35 ft below the small unconformity at the base of the "B" limestone.

Loxostomum pakaurangiensis occurs frequently in the Rifle Butts Formation at Oamaru and it has been found in top part of the Caversham sandstone, 200 ft below the Goodwood limestone, north of Dunedin (F6333).

At Clifden, *L. pakaurangiensis* is common in the type Altonian but has not been found above the Lillburnian. In Westland it occurs in the lower part of the Southland Series, e.g., in the basal Blue Bottom formation (Altonian) exposed in Whisky Creek, Waimea Survey District, and it has been found in the basal part of the Tarakohe Marl (F5056, Awamoan) in N.W. Nelson. Along the east coast of the North Island, *L. pakaurangiensis* is common in the Ihungia formation (Altonian and Clifdenian) and occurs in the upper part of the Tutamoe formation in Pourere Survey District (F5938 (AL114); F6106 (AL430), Waiauan). In Northland, *L. pakaurangiensis* occurs in tuffaceous sandstone (Altonian) at Pakaurangi Point, Kaipara Harbour, but it has not been found in the Waitemata Beds around Auckland city.

KNOWN RANGE: Awamoan to Waiauan (Upper Oligocene or Lower Miocene to Middle Miocene).

Notorotalia wilsoni Hornibrook **n.sp.,** Figs 31, 32, 36.

DESCRIPTION: A large, flattened *Notorotalia* with very strongly recurved sutures on both the ventral and dorsal sides. Dorsal side strongly convex, ventral side nearly flat, often slightly concave. The chambers are narrow, numbering 10 to 12 in the final whorl in adults and are ornamented with strong ribs connecting the spiral sutures on the dorsal side and the radial sutures on the ventral side. The periphery bears a strong, sharp keel interrupted in some individuals by irregular, short, rounded glassy spines.

DIMENSIONS OF HOLOTYPE: greatest diameter, 0·93 mm;
greatest height, 0·26 mm.

VARIABILITY: The considerable variability typical of *Notorotalia* is evident in *N. wilsoni* especially in the erratic development of peripheral spines which are nearly absent in some populations, strong in others.

TYPES: New Zealand Geological Survey Catalogue No. TF1330, holotype and 33 paratypes.

TYPE LOCALITY: S68/556, F7890, N.Z.M.S. 1, Sheet S68 (edit. 1950), grid ref. 075178, Weka Creek, 10 ch above the main road bridge in Weka Pass, fine sandstone below the *Neothyris* shell bed and 75 ft below the "E" limestone.

TYPE LEVEL: Muddy sands between the "D" and "E" limestones, Mt. Brown Beds, Altonian Stage (Lower Miocene).

REMARKS: Distinguished by the broad, flattened shell, convex dorsally with very strongly recurved chambers and irregular peripheral spines. Named after Mr D. D. Wilson who collected the type sample in the course of his work on the geology of the Waipara District. *Notorotalia wilsoni* may be derived from *N. serrata* Finlay by the suppression of the very prominent flange-like keel and peripheral spines characteristic of the latter species which is known only from the Landon and Pareora Series.

DISTRIBUTION: *Notorotalia wilsoni* is common in the type Altonian at Clifden and has been found in the type Clifdenian as well. It appears in the beds above the creamy calcareous sandstone at the top of the "D" limestone in the Mt. Brown beds, replacing *N. spinosa* (Chapman) common in the lower part of the sequence and is accompanied by *Heterostegina* sp. and *Planorbulinella zelandica*. In view of the persistence of the typically Hutchinsonian and Awamoan form, *Notorotalia aranea* n.sp. throughout the "D" limestone into the creamy calcareous sandstone and its immediate replacement thereafter by *Notorotalia wilsoni* and accompanying Southland Series forms, an Altonian age for at least the lower part of the beds between the *Hinnites* shell bed and the creamy calcareous sandstone is reasonably well supported. *Notorotalia wilsoni* is common in the *Neothyris* shell bed and persists upwards into the *Hinnites* bed (S68/656, F8993) of Waiauan age (with *Loxostomum truncatum* Finlay). Further east, in the Motunau district, *Notorotalia wilsoni* has been found in the following two localities accompanied by *Cibicides thiaracuta* n.sp., an index species for Southland and Taranaki Series on the east coast of the North Island: S69/241, F5689 collected by Mr B. W. Collins and described as "upper part of Mt. Brown beds", a hard grey mudstone in Smothering Gully, and S69/513, F11284, from the Motunau River section, immediately below the wavey contact between (lower) light grey sandstone and creamy sandstone, N.Z.M.S. 1, Sheet, S69 (edit. 1950), grid ref. 382159. The occurrence of *N. wilsoni* and *C. thiaracuta* in the latter locality, conformably overlying Hutchinsonian and Awamoan microfaunas (*Notorotalia serrata*, *N. aranea* n.sp., *Globorotalia miozea* and *zealandica* n.sp., *Discopulvinulina turgida* (Finlay)) and underlying a Lillburnian microfauna (*Orbulina universa*, etc.), confirms the evidence for the Altonian age of the beds between the

Hinnites shell bed and the top of the "D" limestone at Weka Pass.

KNOWN RANGE: Altonian to Waiauan (Lower to Middle Miocene).

Notorotalia aranea Hornibrook, **n.sp.,** Figs 12–14.

1946 *Notorotalia* n.sp. aff. *tenuissima* (Karrer): Finlay, in Wellman, Trans. roy. Soc. N.Z. 75 (2) : 233.

DESCRIPTION: Exceedingly small, flattened, *Elphidium*-like, with numerous narrow recurved chambers, about 15 in the final whorl. The surfaces are ornamented with dense fine ribs connecting the sutures, producing a spider-web effect. The coiling is involute on what is apparently the ventral side whereas the dorsal side is slightly evolute. No distinct aperture has been observed although there is a suggestion of one at the base of the final chamber.

DIMENSIONS OF HOLOTYPE: greatest diameter, 0·35 mm;
thickness, 0·07 mm.

VARIABILITY: Except for a difference in size at different localities, this species is very constant in its characteristics. It never reaches the size of adult *N. tenuissima* (Karrer) which usually accompanies it.

TYPES: New Zealand Geological Survey Catalogue No. TF1331; holotype and 9 paratypes.

TYPE LOCALITY: F6491, Old Rifle Butts section, Oamaru, N.Z.M.S. 1, Sheet S136 (Provisional edit., 1943) grid ref. 540629, one foot above the base of the glauconitic sandstone overlying the lower concretionary bed above the brachiopod greensand. Collected by J. Marwick.

TYPE LEVEL: Rifle Butts Formation, Awamoan Stage (Upper Oligocene or Lower Miocene).

REMARKS: Distinguished from the closely related *N. tenuissima* (Karrer) by its smaller size and finer, denser oramentation. The location of this species in *Notorotalia* appears to be justified because of its close affinities with *N. tenuissima* which in its adult form approaches much more nearly to the Oligocene Notorotalias with which it appears to share a common ancestor.

DISTRIBUTION: Widely distributed along the east coast of the South Island in the Hutchinsonian and Awamoan. In the middle Waipara River section below Doctors Gorge, *Notorotalia aranea* first appears in fine sandstone below the "C" limestone (S58/592, F8951) accompanied by *Plectofrondicularia parri* Finlay, and *Virgulopsis pustulata* Finlay, a typically Hutchinsonian assemblage, and continues as a frequent species throughout the Mt. Brown beds up to and including the "D" limestone. In the Weka Creek section, *N. aranea* appears in the middle of the Grey Marls (S68/664, F9100), 300 ft below the base of the "B" limestone, accompanied by *Plectofrondicularia parri*, and occurs in most samples collected higher in the section, making its highest appearance in the 10 ft creamy calcareous sandstone at the top of the "D" limestone, well exposed in Weka Pass Stream (N.Z.M.S. 1, Sheet S68(edit., 1950), grid ref. 077186, sample S68/34, F6639). The muddy sands between the "D" limestone and the *Hinnites* bed contain an Altonian microfauna with *Planorbulinella zelandica* Finlay, *Notorotalia wilsoni* n.sp., etc.

Further east, in the Motunau River section, *N. aranea* is present in S69/507, F8939, 70 ft above the "Amuri" limestone in a Hutchinsonian microfauna that includes *Haeuslerella* aff. *pukeuriensis*, *Robulus echinatus*, *Virgulopsis pustulata*, *Plectofrondicularia parri*, *Notorotalia serrata*, *Discopulvinulina turgida*, *Sherbornina?* small n.sp. and abundant Globigerinidae but is notably lacking in *Globorotalia*.

In South Canterbury, *N. aranea* is present in both Hutchinsonian and Awamoan microfaunas from the Mt. Harris beds.

It is present in the Oamaru district in the type Hutchinsonian at Hutchinson's Quarry (in the conglomerate) and in the type Awamoan at Awamoa Creek and is one of the characteristic species of the Rifle Butts Formation.

The upper part of the Caversham Sandstone (Hutchinsonian and Awamoan) and the Goodwood limestone (Awamoan) in the Dunedin district, both contain frequent *N. aranea*. A possible occurrence of *N. aranea* in the Otaian part of the Caversham Sandstone at Green Island cemetery, just above the brachiopod bed (F6279), has to be recorded here. The single broken specimen from this locality unfortunately does not permit certain identification.

The only record of *N. aranea* from Southland is from the matrix of Mollusca (F5140) collected by Hector from a locality described as Pourakino, near Riverton. The associated microfauna is a shallow water type of assemblage such as is found from Landon to Southland time but it includes *Planorbulinella plana* and small *Globorotalia miozea*, neither of which occur earlier than Awamoan. Because of its resemblance to Awamoan assemblages on the east coast of the South Island, an Awamoan age has been assumed for the Pourakino microfauna.

Two West Coast localities at which *N. aranea* has been found can be recorded here. The first is from a calcareous sandstone (S37/531, F6383) in the headwaters of the Fox River described by Wellman (1946, p. 233). *Virgulopsis pustulata* and *Plectofrondicularia parri* also occur in this fauna, the assemblage being typically Hutchinsonian. The second locality is Shag Creek (N.Z.M.S. 1, Sheet S31 (Provisional edit., 1944) grid ref. 324487, sample S31/517, F6437) where *N. aranea* occurs in a dark micaceous mudstone together with *Plectofrondicularia parri* and a rather indeterminate assemblage that appears to be of Hutchinsonian age.

N. aranea has not been found in the North Island.

The distribution of this distinctive little form, one of the most characteristic elements of Hutchinsonian and Awamoan microfaunas, has an important bearing on the problem of the validity of these stages and their relationship to the lower Southland Series.

Perhaps it is significant that *N. aranea* is usually found in sandy lithologies, suggesting that it is characteristic of a particular facies rather than a particular age. The disappearance of this species above the "D" limestone in the Mt. Brown beds, does not, however, seem related to any marked facies change, nor does its appearance, lower in the same sequence. Sandy lithologies are widespread in the Southland Series but *N. aranea* has not so far been found in beds with Southland microfaunas.

KNOWN RANGE: Otaian? Hutchinsonian to Awamoan (Upper Oligocene or Lower Miocene).

Globigerina pseudoiota Hornibrook, Figs 23, 26–28.

1958 *Globigerina pseudoiota* Hornibrook, Micropaleontology 4 (1): 34, Plate 1, figs 16-18.

A collection made recently by the writer from 20 ft above the base of the Dannevirke Series at the mouth of Birch stream (S68/781, F11279, N.Z.M.S. 1, Sheet S68 (edit., 1950), grid ref. 989143) yielded excellent specimens of *G. pseudoiota*, considerably better preserved and more abundant than the type material. This opportunity has been taken to illustrate further specimens showing the distinctly asymmetrical coiling and aperture and the inflated rounded shape of the chambers. Figure 23 illustrates the sutures, only slightly recurved, in contrast to the sutures of *Globigerina iota* (Finlay) (Fig. 20) which are distinctly recurved.

The specimens of *G. pseudoiota* illustrated in the present paper are of either Waipawan or Mangaorapan age (Paleocene or lowermost Eocene) and their marked asymmetry is typical of the whole sample from which they were selected. Higher in the section, however, in the bentonitic mudstone of Heretaungan age (Lower Eocene), sample F5675 contains individuals of a population in which both symmetrical and asymmetrical forms occur. In the more compressed, narrower, smaller test and recurved sutures they resemble *iota* more than *pseudoiota* yet in the occurrence of distinctly asymmetrical specimens they are intermediate between the two.

There can be little doubt that *G. pseudoiota* is the ancestor of the species described as *Nonion iota* by Finlay from the Bortonian (Middle Eocene) at Moeraki (F5300), Finlay's specimens, as noted above, being almost perfectly symmetrical and more compressed than *G. pseudoiota*. In his desecription of "*Nonion*" *iota*, Finlay (1940, p. 456), noted its close resemblance to *Nonion micrus* Cole and *N. danvillense* Howe, described from the Eocene of North America. *Globigerinella pseudovoluta* Bandy may be added to this group and it is very likely that all four if not synonymous, are at least closely related. Most authors have described these Eocene forms merely as planispiral but in a sample of 45 specimens of *N. micrus* from the Aragon Formation of Mexico, examined by the writer, many individuals exhibited slight asymmetry both in coiling and aperture, as does the New Zealand form, *iota*.

Nonion micrus and *N. danvillense* were considered synonyms by Glaessner (1937a : 30) who placed them in *Globigerinella*. This was the genereic name used for the group by most subsequent authors until Bolli (1957c : 161) changed the generic status to *Hastigerina* of which he considered *Globigerinella* a junior synonym.

The generic status of this little group is questionable as the New Zealand Eocene member, as shown above, has developed from a Paleocene to Lower Eocene form for which *Globigerina* seems to be the appropriate genus. Apart from the greater degree of symmetry, there is little to distinguish *iota* and similar species from *Globigerina*.

Hastigerina, with the Recent *H. pellagica* Brady as its type species, is inappropriate for the group of Eocene species under discussion. The closely related *H. aequilateralis* (Brady) was also described from Recent specimens, both species possibly having developed during the Pliocene or Miocene. Unlike the tiny, slightly asymmetrical Eocene species assigned to *Hastigerina*, the two Recent species are relatively large and perfectly symmetrical and have coarsely porous or spiney tests.

A probable third group is formed by Cretaceous species such as *Globigerinella messinae* Bronniman and *G. aissana* Sigal.

In the present state of knowledge it might be premature to split the Cretaceous group from *Hastigerina* which should continue to be used as a form genus until the origins of the different groups are better understood.

The small group of Eocene species discussed above, of which at least *iota* has developed from an asymmetrical *Globigerina*-ancestor, are better included in *Globigerina* for the present.

Globigerina gravelli Bronniman, Figs 21, 25.

1952 *Globigerina gravelli* Bronniman; Bull. Amer. Paleont., 34 (143) : 12-13, pl. 1 figs 16-18.

1957 *Globigerina gravelli* Bolli; Bull. U.S. nat. Mus. 215 : 72, pl. 16, figs 1-3.

Numerous specimens of *Globigerina gravelli* were found in a sample (S68/773, F11271) collected by the writer from a mudstone at the base of the Dannevirke Series, 2 ft above the top of the Waipara Greensand in the Waipara River, at the mouth of Birch Stream (N.Z.M.S. 1, Sheet S68 (edit., 1950) grid ref. 989143). The individuals in this sample closely resemble the figures and description of *G. gravelli* by Bronniman who found it throughout the Paleocene-Lower Eocene Lizard Springs Formation, Trinidad, accompanied by *G. soldadoensis* Bronniman, and in the Ramdat Marl. Bolli (1957a) : 63, 66, 72), however, gives the range of *G. gravelli* as within the upper part of the Lizard Springs Formation.

The specimens from the Waipara closely resemble those from Trinidad in being larger than *G. soldadoensis* which accompanies them, and in being coarsely spinose (the specimen figured here is rather more spinose than average).

DIMENSIONS OF FIGURED SPECIMEN: greatest diameter, 0·50 mm.

N.Z. GEOLOGICAL SURVEY CATALOGUE NO. OF FIGURED SPECIMENS: FP1107.

AGE OF FIGURED SPECIMEN: Waipawan Stage (Paleocene).

KNOWN RANGE IN NEW ZEALAND: Waipawan Stage (Paleocene).

Globigerina soldadoensis Bronniman, Figs 22, 29.

1952 *Globigerina soldadoensis*, Bronniman; Bull. Amer. Paleont. 34 (143): 9-11, pl. 3, figs 1-9.

1957 *Globigerina gravelli*, Bolli; Bull. U.S. nat. Mus. 215: 71, pl. 16, figs 7-12.

Two samples (S68/773, F11271; F5668) from the base of the Dannevirke Series in the Middle Waipara section contained an abundant spinose *Globigerina* identical, judged by the figures and descriptions, with *G. soldadoensis* described by Bronniman from the Lizard Springs Formation, Soldado Formation and Ramdat marl of Trinidad. The last whorl consists of 4 to 5 chambers ornamented with fine spines, much less prominent than in *G. gravelli*. The test is somewhat smaller than in *gravelli*.

According to Bronniman, *G. soldadoensis* is one of the most characteristic Globigerinidae of the Trinidad Paleocene although Bolli (1957a, pp. 63, 66, 71) gives its range as *Globorotalia velascoensis* zone to *Globorotalia aragonensis* zone, Lizard Springs Formation, continuing into the Navet Formation (i.e., Paleocene to Lower Eocene).

Accompanying *G. soldadoensis* and *gravelli* in the basal part of the Dannevirke Series at the mouth of Birch Creek is a typically Paleocene assemblage including *Globorotalia aequa* Cushman and Renz, *Globorotalia crater* Finlay (aff. *velascoensis*), *G. pseudomenardii* Bolli, *Globigerina pseudobulloides* Plummer, *G. triloculinoides* Plummer and *Aragonia* sp.

The occurrence of *G. soldadoensis* and *gravelli* in the New Zealand lower Dannevirke Series is additional evidence for the close relationship between Paleocene and Lower Eocene microfaunas of New Zealand and the Central American region pointed out previously by Hornibrook (1953, p. 439).

DIMENSIONS OF FIGURED SPECIMEN: greatest diameter, 0·50 mm.

N.Z. GEOLOGICAL SURVEY CATALOGUE NO OF FIGURED SPECIMEN: FP1108.

LOCALITY OF FIGURED SPECIMEN: S68/199, F5668, Middle Waipara River, 30 ch N.W. of Gorge, left bank; base of Dannevirke Series. Collected by Mr J. Healy.

AGE OF FIGURED SPECIMEN: Waipawan Stage (Paleocene).

KNOWN RANGE IN NEW ZEALAND: Waipawan Stage (Paleocene).

Globorotalia zealandica Hornibrook, **n.sp.,** Figs 18, 19, 30.

DESCRIPTION: Adult test made up of two whorls of inflated, rounded chambers, 4 in the final whorl. The chambers are as high as they are wide, being broadly and evenly rounded in edge view, without any trace of a keel; the sutures on the highly domed ventral side are slightly recurved but on the almost flat dorsal side they turn backwards at a more acute angle. Surfaces densely porous and smooth except for small tubercles developed on the ventral side of the early chambers of the last whorl. Aperture a high arched opening in the terminal face of the last chamber, extending into the umbilical area.

DIMENSIONS OF HOLOTYPE: diameter, 0·43 mm;
height, 0·29 mm.

VARIABILITY: In the type sample the ratio of coiling directions is 5 anticlockwise to 2 clockwise.

TYPES: New Zealand Geological Survey Catalogue No TF1332; holotype and 67 paratypes.

TYPE LOCALITY: S137/499, F5125, Pukeuri Road cutting four miles N.N.E. of Oamaru; N.Z.M.S. 1, Sheet S137 (Provisional edit., 1943), grid ref. 591743.

REMARKS: Distinguished from *Globorotalia miozea* Finlay, which it frequently accompanies, by the rounded, inflated, unkeeled test. *G. zealandica* belongs within the subgenus *Turborotalia* as defined by Cushman and Bermudez. These authors, however, cited as type species *Globorotalia centralis*, which is the solitary Eocene *Turborotalia*, there being no known members of the subgenus in the lower and middle Oligocene. The Globorotalias related to *G. menardii* appearing in the upper Oligocene and lower Miocene, accompanied by *Turborotalia*-like forms, such as *G. zealandica*, may well have developed independently from a *Globigerina* stock through intermediate forms such as *Globorotalia mayeri* and may be unrelated to the Eocene species. The position of the subgenus *Truncorotalia* Cushman and Bermudez, is rather similar to that of *Turborotalia*. The common Recent and Pliocene and possibly upper Miocene species, *Globorotalia truncatulinoides*, was cited as the type species of *Truncorotalia* and there is evidence to suggest that this species developed from a *menardii*-like *Globorotalia* during the upper Miocene in New Zealand. The compact group of Paleocene to Middle Eocene *Truncorotalia*-like species (*velascoensis*, *aragonensis*, *acuta*, etc.) which are included in *Truncorotalia* are certainly unrelated to *G. truncatulinoides* and if foraminiferal genera are to have any phylogenetic basis, ought to be assigned to a separate genus or subgenus.

DISTRIBUTION: Frequent in the Awamoan and Altonian siltstone in the Motunau and Dovedale districts (e.g., Dovedale Stream, S68/648; Motunau River section, S69/16). At Oamaru it is common in the Rifle Butts Formation (Awamoan) and it has been found in the top 200 ft of Caversham sandstone north of Dunedin. On the West Coast of the South Island it occurs in the basal Blue Bottom (F5713, Altonian) in Tansey Creek. It occurs also in the lower part of the Takaka marl at Takaka Quarry, N.W. Nelson (F5056, Awamoan). Along the east coast of the North Island *Globorotalia zealandica* is common in some localities in the lower part of the Ihungia Formation (Altonian) and it also occurs in the Altonian in the lower part of the Midhirst No 1 Well, in Taranaki, and in the Mokau Sandstone (Altonian). So far it has not been found together with *Orbulina,* nor does it occur in the Hutchinsonian.

KNOWN RANGE: Awamoan to Altonian (Upper Oligocene to Lower Miocene).

Cibicides thiaracuta Hornibrook, **n.sp.,** Figs 33–35.

DESCRIPTION: Large and thick-shelled with very strongly recurved sutures both dorsally and ventrally; surfaces finely and densely porous. Early whorls elevated on the dorsal side to form a prominent dome, the final whorl of adults flattening out. Adults have 10 chambers in the final whorl. Shell compressed at the periphery as seen in edge view, ventral side gently convex, typically without a marked central concavity. Aperture at base of final chamber, running from just below and over the periphery, backwards on the dorsal side for about half the width of the chamber. The aperture is bordered by a distinct lip and traces of previous apertures are preserved along the spiral suture at the bases of the final three or four chambers.

DIMENSIONS OF HOLOTYPE: greatest diameter, 1·54 mm;
height, 0·54 mm.

VARIABILITY: The convexity of the dorsal surface is typically strong but is subject to some variation and relatively depressed and flattened individuals are met with.

TYPES: New Zealand Geological Survey Cat. No. TF1333; holotype and 10 paratypes.

TYPE LOCALITY: F11413, GS1342, Patutahi S.D., Block 2, Waikura Stream, 2 miles 60 ch E.S.E. of Poha Trig.

TYPE LEVEL: Tutamoe Formation, Lillburnian Stage (Middle Miocene).

REMARKS: Very similar to the earlier *Cibicides thiara* (Stache) (Upper Arnold Series to Waitakian), from which it appears to be descended. *C. thiaracuta* differs from *thiara* in its consistently larger size, in its more acute periphery, in having more strongly recurved chambers and in lacking the distinct depressed area typically developed in the centre of the ventral side in *C. thiara*.

DISTRIBUTION: In North Canterbury, *C. thiaracuta* occurs in the Motunau River section (S69/513, F11284) together with *Notorotalia wilsoni* n.sp. above an upper Pareora Series sandstone and is abundant higher in the same section in a middle Southand Series microfauna. *C. thiaracuta* is also present together with *Notorotalia wilsoni* n.sp. in an Altonian microfauna (S68/241, F5689), collected in Smothering Gully. Grey siltstone in Cheviot Survey District contains *C. thiaracuta* in a good Tongaporutuan microfauna (*Bolivinita pohana* Finlay, etc.). *C. thiaracuta* is frequent in the Southland Series on the West Coast of the South Island (e.g., in Whisky Creek section).

On the east coast of the North Island *C. thiaracuta* occurs commonly in the Southland Series (the Ihungia and Tutamoe formations) and less frequently in the Tongaporutuan (e.g., GS1332, Waikohu Survey District).

There are few records of *C. thiaracuta* from Taranaki. It has been found in the middle to upper Southland Series near Tirua Point (F5582), in the conglomerate at the base of the Mohakatino Formation at the old quarry 1 mile north of Mokau (GS2935) and in the New Zealand Petroleum Company's Uruti No 2 well.

The distribution of *C. thiaracuta*, chiefly occurring in the areas of geosynclinal Southland Series, suggests that it inhabited moderately deep water.

KNOWN RANGE: Altonian to Tongaporutuan (Lower to Upper Miocene).

Pseudoclavulina anglica Cushman, Figs 1–2.

FIG. 1.—Specimen (N.Z.G.S. Cat. No FP1101) from F5934, Waipawa; × 20.

FIG. 2.—Apertural view of specimen (N.Z.G.S. Cat. No FP1102) from F5934; × 20.

Sigmoilopsis neocelata Hornibrook, **n.sp.,** Figs 3, 4, 10.

FIG. 3.—Holotype (N.Z.G.S. Cat. No. TF1325/1), F6230, basal Blue Bottom, Fletcher Creek; × 40.

FIG. 4.—Holotype, apertural view; × 60.

FIG. 10.—Transverse section of a specimen (N.Z.G.S. Cat. No FP1103) from F5969, Blue Bottom; × 100.

Sigmoilopsis compressa Hornibrook, **n.sp.,** Figs 5, 6, 11.

FIG. 5.—Aperture of holotype (N.Z.G.S. Cat. No TF1326/1), F8276, Dovedale siltstone; × 40.

FIG. 6.—Holotype; × 60.

FIG. 11.—Transverse section of paratype (N.Z.G.S. Cat. No TF1326/2); × 100.

Buliminella waiparaensis Hornibrook, **n.sp.,** Figs 7–9.

FIG. 7.—Paratype (N.Z.G.S. Cat. No TF1327/2), F5329, east branch, Grey River; × 100.

FIG. 8.—Holotype (N.Z.G.S. Cat. No TF1327/1); × 100.

FIG. 9.—Apertural view of paratype (N.Z.G.S. Cat. No TF1327/2); × 100.

Notorotalia aranea Hornibrook, **n.sp.,** Figs 12–14.

FIG. 12.—Holotype (N.Z.G.S. Cat. No TF1331/1), evolute side F6491, Old Rifle Butts, × 100.

FIG. 13.—End view of holotype; × 100.

FIG. 14.—Involute side of holotype; × 100.

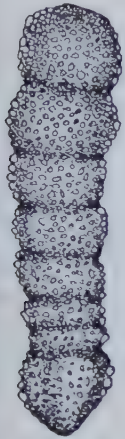
Bolivina fyfei Hornibrook, **n.sp.,** Figs 15, 16.

FIG. 15.—Holotype (N.Z.G.S. Cat. No TF1328/1), F7030, Hundalee; × 100.

FIG. 16.—Holotype, edge view; × 100.

Loxostomum pakaurangiensis Hornibrook, **n.sp.,** Fig. 17.

FIG. 17.—Holotype (N.Z.G.S. Cat. No TF1329/1), F11414, Pakaurangi Point; × 100.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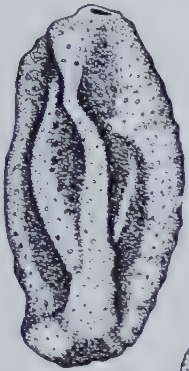
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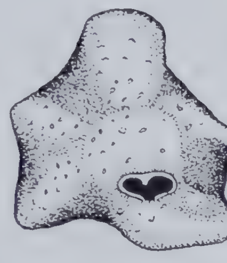
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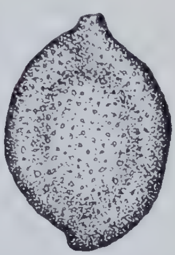
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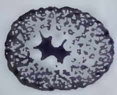
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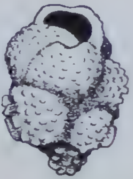
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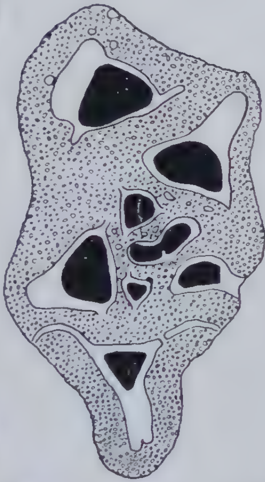
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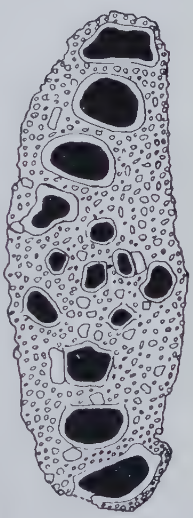
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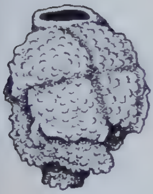
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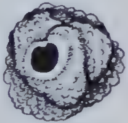
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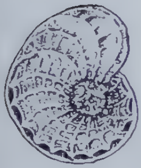
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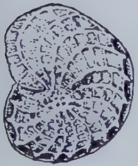
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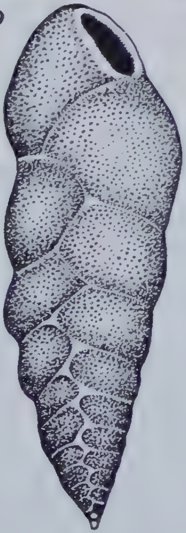
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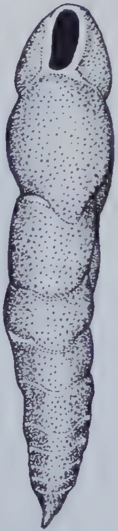
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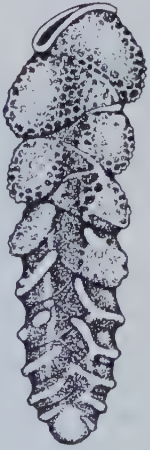
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Globorotalia zealandica Hornibrook, **n.sp.,** Figs 18, 19, 30.

FIG. 18.—Ventral side of holotype (N.Z.G.S. Cat. No TF1332/1), F5125, Pukeuri; × 100.

FIG. 19.—Dorsal side of holotype; × 100.

FIG. 30.—Apertural view of holotype; × 100.

Globigerina gravelli Bronniman, Figs 21, 25.

FIG. 21.—Ventral view of a specimen (N.Z.G.S. Cat. No FP1107) from F11271, Middle Waipara; × 100.

FIG. 25.—Peripheral view of the specimen FP1107; × 100.

Globigerina soldadoensis Bronniman, Figs 22, 29

FIG. 22.—Ventral view of a specimen (N.Z.G.S. Cat. No. FP1108) from F5668, Middle Waipara; × 100.

FIG. 29.—Peripheral view of specimen FP1108; × 100.

Globigerina iota (Finlay), Figs 20, 24.

FIG. 20.—Paratype (N.Z.G.S. Cat. No TF1182/3), F5300, Moeraki; × 100.

FIG. 24.—Peripheral view of paratype (N.Z.G.S. Cat. No TF1182/4); × 100.

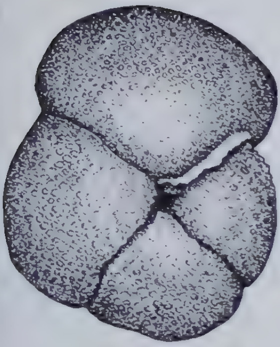
Globigerina pseudoiota Hornibrook, Figs 23, 26–28.

FIG. 23.—A specimen (N.Z.G.S. Cat. No FP1105) from F11279, Middle Waipara; × 100.

FIG. 26.—Specimen FP1105, peripheral view; × 100.

FIG. 27.—Peripheral view of a specimen (N.Z.G.S. Cat. No FP1106) from F11279; × 100.

FIG. 28.—Peripheral view of a specimen (N.Z.G.S. Cat. No FP1104) from F11279; × 100.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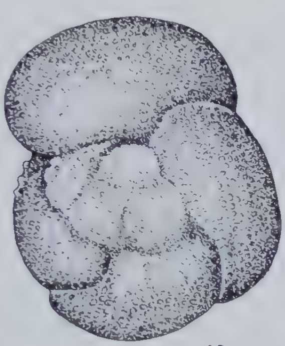
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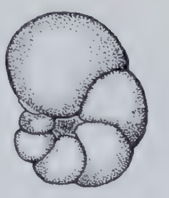
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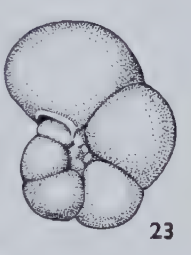
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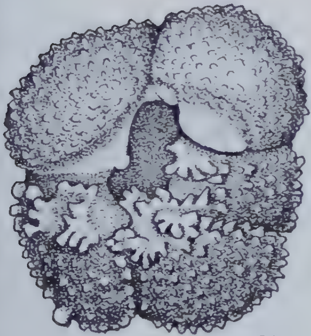
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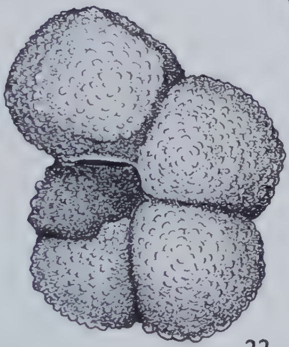
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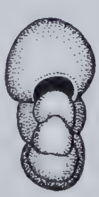
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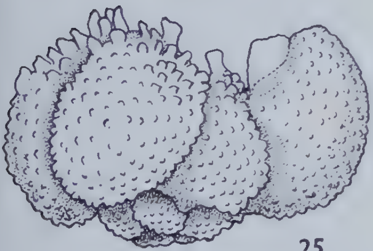
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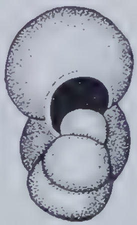
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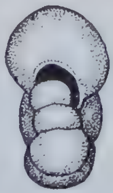
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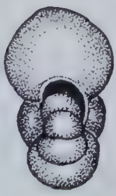
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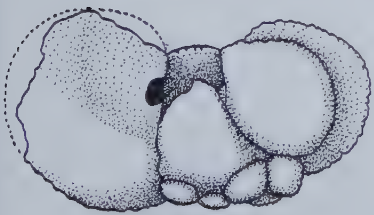
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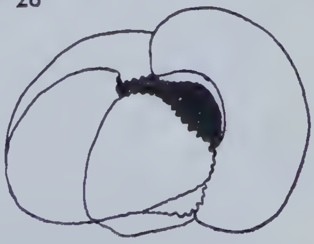
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Notorotalia wilsoni Hornibrook, **n.sp.,** Figs 31, 32, 36.

FIG. 31.—Peripheral view of holotype (N.Z.G.S. Cat. No TF1330/1), F7890, Weka Creek; × 60.

FIG. 32.—Dorsal view of holotype; × 60.

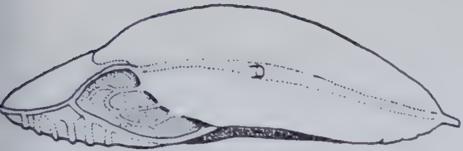
FIG. 36.—Ventral view of holotype; × 60.

Cibicides thiaracuta Hornibrook, **n.sp.,** Figs 33–35.

FIG. 33.—Dorsal view of holotype (N.Z.G.S. Cat. No TF1333/1), F11413, Tutamoe, Waikura Stream; × 60.

FIG. 34.—Peripheral view of paratype (N.Z.G.S. Cat. No. TF1333/2); × 60.

FIG. 35.—Ventral view of paratype (N.Z.G.S. Cat. No TF1333/2); × 60.



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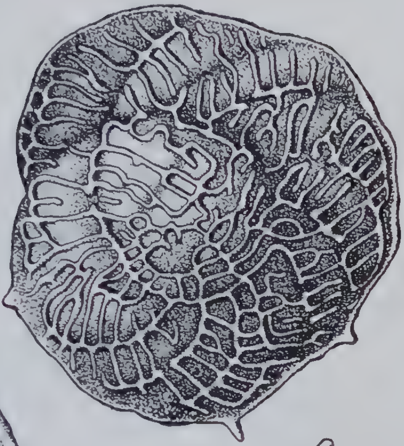

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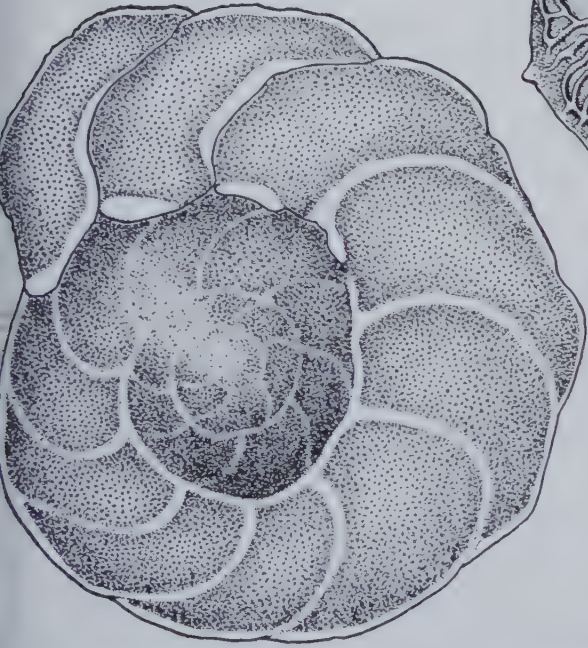

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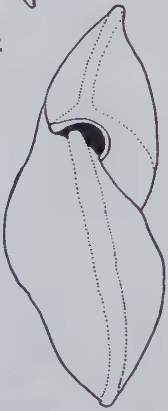

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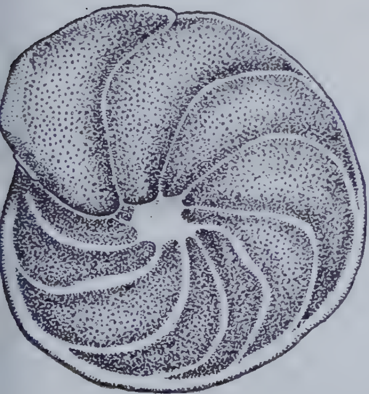

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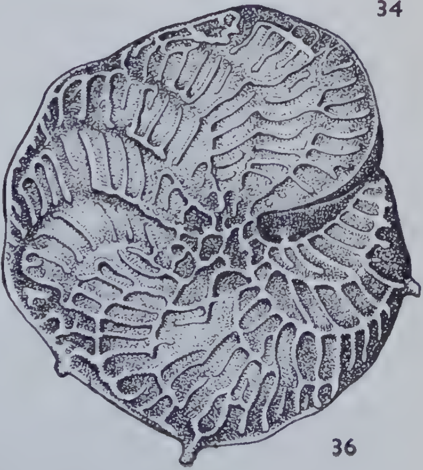

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REFERENCES

BOLLI, H. M., 1957a: The Genera *Globigerina* and *Globorotalia* in the Paleocene-lower Eocene Lizard Springs Formation of Trinidad, B.W.I. *U.S. nat. Mus. Bull. 215* : 61-81.

———, 1957b: Planktonic Foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B.W.I. *U.S. nat. Mus. Bull. 215* : 97-123.

———, 1957c: Planktonic Foraminifera from the Eocene Navet and San Fernando Formations of Trinidad, B.W.I. *Bull. U.S. nat. Mus. 215* : 155-72.

BROTZEN, F., 1948: The Swedish Paleocene and its Foraminiferal Fauna. *Sverig. geol. Unders., Afh. Ser. C, No. 493,* 140 pp.

CUSHMAN, J. A., 1937: A Monograph of the Foraminiferal Family Verneuilinidae. *Spec. Publ. Cushman Lab. No. 7,* 157 pp.

FINLAY, H. J., 1939a: New Zealand Foraminifera: Key Species in Stratigraphy—No. 1. *Trans. roy. Soc. N.Z. 68* : 504-33.

———, 1939b: N.Z. Foraminifera: The Occurrence of *Rzehakina, Hantkenina, Rotaliatina,* and *Zeauvigerina. Trans. roy. Soc. N.Z., 68*: 534–43.

———, 1939c: New Zealand Foraminifera: Key Species in Stratigraphy—No. 2. *Trans. roy. Soc. N.Z., 69 (1)* : 89-128.

———, 1939d: New Zealand Foraminifera: Key Species in Stratigraphy—No. 3. *Trans. roy. Soc. N.Z., 69 (3)* : 309-29.

———, 1940: New Zealand Foraminifera: Key Species in Stratigraphy—No. 4. *Trans. roy. Soc. N.Z., 69 (4)* : 448-72.

———, 1947: New Zealand Foraminifera: Key Species in Stratigraphy—No. 5. *N.Z. J. Sci. Tech. B28 (5)* : 259-92.

FINLAY, H. J.; MARWICK, J., 1940: The Divisions of the Upper Cretaceous and Tertiary in New Zealand. *Trans. roy. Soc. N.Z., 70 (1)* : 77-135.

———, 1947: New Divisions of the New Zealand Upper Cretaceous and Tertiary. *N.Z. J. Sci. Tech. B28 (4)* : 228-36.

———, 1948: Cretaceous and Tertiary. *in* "The Outline of the Geology of New Zealand". (To accompany the 16 mile to 1 inch geological map.) N.Z. Geological Survey, Wellington.

GLAESSNER, M. F., 1937a: Planktonforaminiferen aus der Kreide und dem Eozan und ihre Stratigraphische Bedeutung. *Stud. Micropaleont. Moscow, 1 (1)* : 27–46.

———, 1937b: Studien ueber Foraminiferen aud der Kreide und dem Tertiaer des Kaukasus; Part 1; Die Foraminiferen der Aeltesten Tertiaerschichten des Nordwestkaukasus. *Probl. Paleont. Moscow 2, 3* : 349–410.

HORNIBROOK, N. de B., 1953: Faunal Immigrations to New Zealand; Part 1; Immigration of Foraminifera to New Zealand during the Upper Cretaceous and Tertiary. *N.Z. J. Sci. Tech. B34 (6)* : 436-44.

———, 1958: New Zealand Upper Cretaceous and Tertiary Foraminiferal Zones and Some Overseas Correlations. *Micropaleontology, 4 (1)* : 25–38.

WELLMAN, H. W., 1946: Geology of Fox River Headwaters, Brighton Survey District, South-west Nelson. *Trans. roy. Soc. N.Z. 76 (2)* : 211-36.

MOUNTAIN WAVES OVER BANKS PENINSULA, NEW ZEALAND

By Edith Farkas, New Zealand Meteorological Service, Wellington

(Received for publication, 4 August 1958)

Summary

Twenty-seven occurrences of wave motion in the atmosphere over the hilly terrain of Banks Peninsula, South Island, New Zealand, have been analysed from the Christchurch radiosonde and radar wind records. The average maximum vertical velocity found was approximately 1,000 ft per min., but velocities up to 2,000 ft per min. were found to occur occasionally. The conditions in which these waves may exist and some of their characteristic properties are given.

INTRODUCTION

It has been common knowledge for a number of years among New Zealand pilots that strong ascending and descending air currents frequently occur on the lee-side of the Southern Alps and the Kaikoura Ranges. More recently, these currents have been recognized as caused by wave motions in the atmosphere to the lee of the ranges in the South Island of New Zealand. Amateur gliding associations have reported record flights in these waves, and recently some spectacular flights have been made, one reaching 25,000 ft in height and more than 200 miles in range.

This paper presents results of analysis of two years of radiosonde and radar wind data taken at Christchurch Airport (S °43 29′ E 172° 32′). The station is situated on the Canterbury Plains, to the south-east of the main ranges, from which point the radiosonde and radar wind observations were expected to yield information concerning mountain waves occurring in the vicinity of Christchurch.

TOPOGRAPHY

The Southern Alps and the Kaikoura Ranges, forming a barrier between the western and eastern coasts of the South Island of New Zealand are regarded for the present purpose as one range lying approximately south-west–north-east. North-west from Christchurch, individual peaks rise to 6,000 ft. It would be expected that favourable conditions for the formation of lee-waves would occur when north-west winds (i.e., at right-angles to the direction of the range) prevail through a deep tropospheric layer. Under these conditions, however, the paths of the

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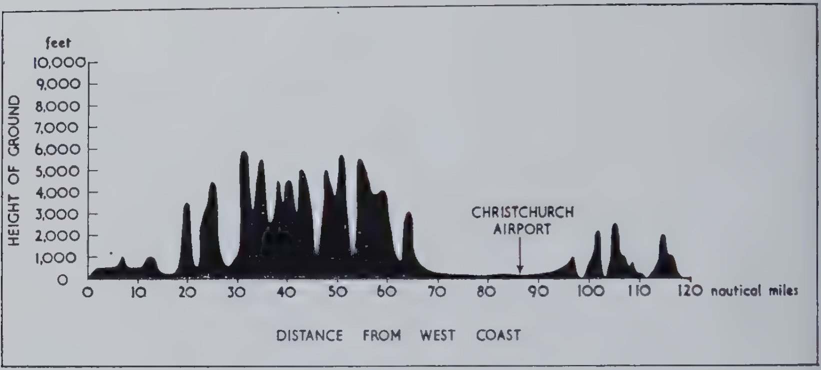

FIG. 1.—Approximate topographical cross-section of the South Island of New Zealand in a NW–SE line through Christchurch Airport.

sounding balloons would lie over Banks Peninsula, south-east of Christchurch. This is also an area of hilly country, although the highest peak rises to only 3,000 ft. A north-west–south-east cross-section of the South Island is shown in Fig. 1.

DATA AND METHOD OF ANALYSIS

Routine upper air observations at Christchurch Airport during the period investigated consisted of one radiosonde observation combined with radar wind observations at 0400 G.M.T. (1600 N.Z.S.T.) daily, and radar wind observations alone at 1000, 1600, and 2200 G.M.T. The vertical air currents that influence the ascending velocity of the balloon were estimated from observed anomalies in the rate of ascent of the balloon. Since the height of the balloon at regular intervals is, in general, more accurately determined by radiosonde than by radar observations, all radiosonde flights at Christchurch for the years 1955 and 1956 were first examined for evidence of wave motion. Seventeen ascents indicated the presence of standing waves.

For these seventeen ascents, the vertical velocities were estimated independently from the radar observations that were combined with the radiosonde ascents. The good agreement found between the results obtained independently from the radiosonde and the radar data encouraged extension of the search to the radar wind records for 1000, 1600, and 2200 G.M.T. during the above-mentioned period. From these data another ten occurrences of waves were found.

The 27 occurrences of waves at Christchurch were distributed approximately equally between the summer and winter seasons.

The method of calculating vertical velocities is based on the evaluation of rates of ascent during balloon flights (Reid, 1952; Corby, 1957).

The height of the ascending balloon was calculated at minute intervals from the pressure and temperature signals of the radiosonde, and from range and elevation readings of the radar. Quasi-periodic departures of more than 100 ft per min. from the average rate of ascent were accepted as indications of the presence of atmospheric waves if the weather situation was such that other causes of anomalous ascent rates, such as icing and convection, could be discounted.

ESTIMATION OF STANDARD ERRORS

Standard errors in the processing of data and in the calculation of vertical velocities were estimated for both radiosonde and radar wind observations. For radiosonde data, typical stand errors are shown in Table 1.

TABLE 1.—Variation of Standard Error of Rates of Ascent from Radiosonde Data.

Time from release (min.)	1–3	3–5	5–10	10–15	15–20	20–25	25–30	30–35	35–40
Standard error (%) —	8·7	6·5	7·6	7·6	7·6	9·3	11·8	16·3	18·6

Assuming a nominal rate of ascent of about 1,000 ft per min., departures of 100 ft per min. from the mean rate of ascent are likely to be significant.

For radar wind data, the random error rapidly increased with height, and in most cases reached the magnitude of the observed departures by the twentieth minute of the ascent.

WIND AND STABILITY STRUCTURE

Results of theoretical investigations show that the ability of an airstream to execute wave motion is closely connected with the variation of wind velocity and stability with height (Scorer, 1949, 1953, 1954, 1955; Corby and Wallington, 1956). The dynamical properties of the air at any level may be characterized by a parameter l, the lee-wave constant. It was found that the term involving the second derivative of the wind speed with respect to height could be neglected, so that the expression for l could be reduced to

$$l = \frac{B}{U}$$

$$\text{where } B^2 = \frac{g}{\theta}\frac{\partial \theta}{\partial Z},$$

θ being the potential temperature, Z the vertical co-ordinate, and U the horizontal wind speed. The lee-wave constant for different layers of the atmosphere can thus be calculated from mean horizontal winds and from the stability factor, B. Values of B may be conveniently obtained from the appropriate temperature-height diagram (e.g., tephigram) by means of a suitable scale (Wallington, 1953). The requirement for waves to occur is for l to reach a maximum in the lower troposphere and decrease with height. This requirement is favoured by pronounced stability in the lower layers.

Mean wind-speeds calculated for all 27 instances in which waves occurred showed increasing windspeed up to 10,000 ft, but nearly constant speed in the next 8,000 ft layer. Above the first few thousand feet, the wind direction was in all instances from the north-west. To compare wind and stability structure for instances of occurrence and of non-occurrence of waves, 14 radiosonde ascents during 1955-56 in which wave motion did not occur were selected for analysis. In these 14 cases, the balloons followed paths similar to those in the 17 ascents for which wave motion did occur. Mean values for the relevant parameters of the two groups are shown in Table 2.

TABLE 2.—Values of the Mean Stability Factor B, of the Mean Horizontal Wind Speed U, and of the Mean Lee-wave Constant l for Groups of Occurrence and Non-occurrence of Wave Motion.

Height (1,000 ft)	1–3	3–5	5–7	7–10	10–14	14–18	18–24	24–30
B (hr^{-1})								
Waves	17	13	19	27	36	27	25	26
No waves	22	18	23	28	30	29	24	24
U (kt)								
Waves	18	19	24	36	41	42	49	57
No waves	27	31	37	45	52	53	55	62
l (n.mi.$^{-1}$)								
Waves	0·9	0·7	0·8	0·8	0·9	0·6	0·5	0·4
No waves	0·8	0·6	0·6	0·6	0·6	0·5	0·4	0·4

12345

For the group in which waves occurred, the value of the lee-wave constant l reached a maximum in the 10,000 to 14,000 ft layer and then decreased. For the group in which waves did not occur, no significant increase of l with height was shown. Rather similar vertical distribution of wind-speeds existed in both groups, and the difference in the behaviour of l is thus attributed to the differences in stability structure. The figures, although not conclusive, tend to confirm the validity of Scorer's theoretical criterion for the occurrence of waves.

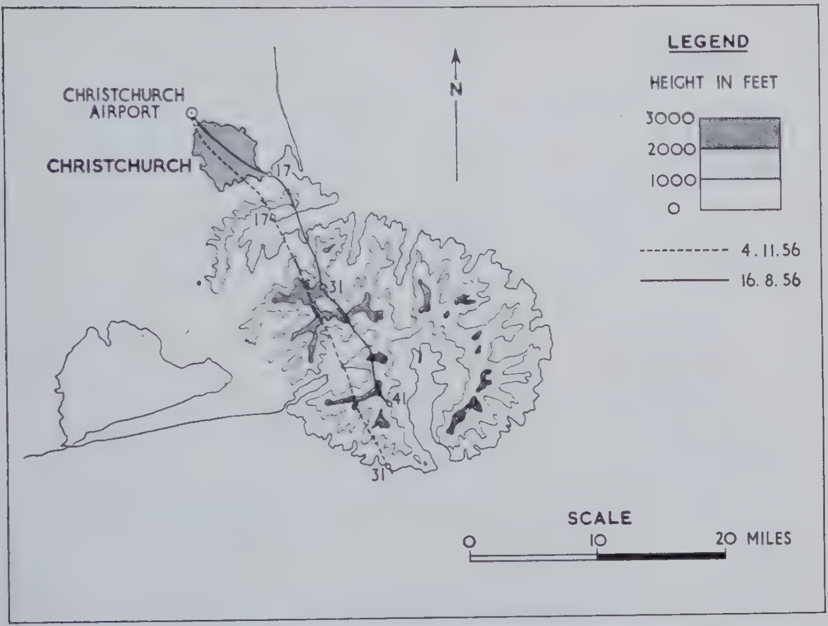

FIG. 2.—Paths of radiosonde balloons over Christchurch and Banks Peninsula at 0400 on 16 August 1956 and 4 November 1956. Numbers indicate times in minutes from release.

EXAMPLES OF WAVE MOTION

Two occasions when large vertical velocities indicated the presence of waves are chosen to illustrate some typical results. Both ascents were combined radiosonde and radar wind flights made at 0400 G.M.T. on 16 August and on 4 November 1956 respectively. Both balloons followed very similar paths, crossing over Christchurch city and Banks Peninsula in a south-eastward direction as shown on Fig. 2. The difference in the wind-speeds encountered by the balloons during the first 41 minutes of their flights on the two occasions is indicated in Fig. 2 by their relative positions over Banks Peninsula. The average horizontal wind-speed throughout the troposphere was approximately 30% higher on the 4 November flight than on the 16 August flight, resulting in a comparatively fast crossing of Banks Peninsula on the former flight.

Figures 3 and 4 show rates of ascent for both radiosonde and radar wind flights versus time from release for each of the above-mentioned ascents. After the first 15 minutes of the radar wind observations, rates of ascent were calculated from two-minute interval readings only. The topographical cross-section of the ground over which the balloon travelled is shown in each figure, and the height of the balloons at every fifth minute is given on each time scale.

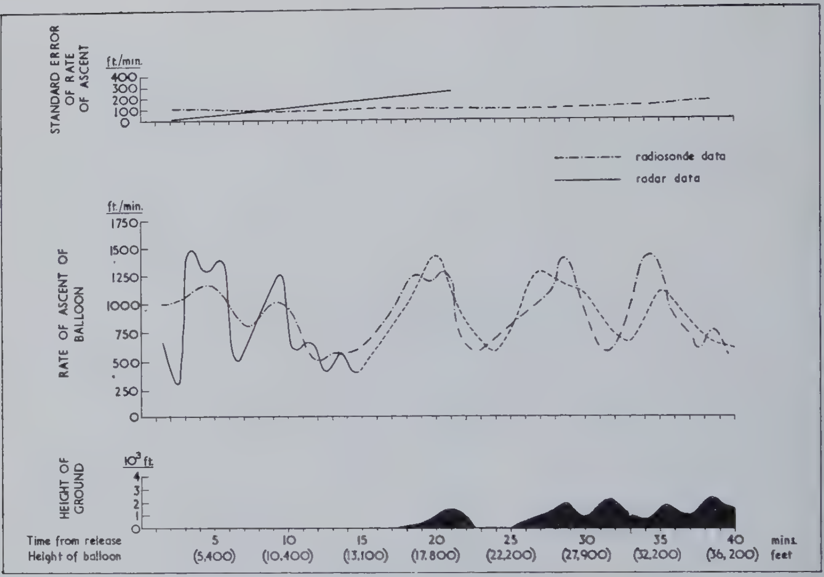

FIG. 3.—Topography, rates of ascent, and standard errors in the estimation of the rates of ascent versus time from release, for the combined radiosonde and radar wind ascent of 0400 G.M.T., 16 August 1956, at Christchurch Airport. Broken lines indicate rates of ascent at two-minute intervals.

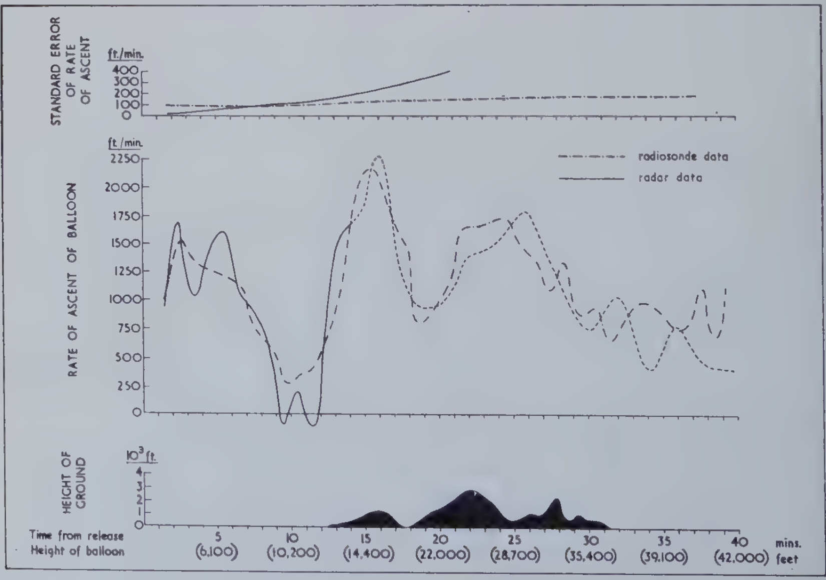

FIG. 4.—Topography, rates of ascent, and standard errors in the estimation of the rates of ascent versus time from release, for the combined radiosonde and radar wind ascent of 0400 G.M.T., 4 November 1956, at Christchurch Airport.

The estimated errors for the radiosonde and radar data separately are also shown. The existence of waves is strongly indicated by the significantly large quasi-periodic vertical velocities encountered by both balloons during their ascents through the troposphere. The balloons entered the stratosphere during the 36th and 30th minute of their flights respectively on 16 August and on 4 November. The locations of ascending and descending currents agreed well with the main topographical features in the case of the 4 November ascent, but on 16 August the upward and downward currents were displaced with respect to the ridges and valleys of the ground profile.

CONCLUSIONS

The presence of orographic wave-motions over Christchurch and Banks Peninsula can be detected in the radiosonde and radar wind data recorded at Christchurch Airport. These disturbances have been found to reach as far up as 32,000 ft in the atmosphere. A detailed examination of the wind and stability structure of tropospheric layers on occasions when wave-motion occurred, and on occasions when wave-motion did not occur, gave results which tend to support the theoretical conclusions of Scorer. It has not been possible to distinguish with certainty between the contributions of Banks Peninsula below and the Southern Alps to the north-west in producing the observed wave-motions.

ACKOWLEDGEMENTS

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REFERENCES

CORBY, G. A.; WALLINGTON, C. E., 1956: Airflow Over Mountains: The Lee Wave Amplitude. *Quart. J. R. met. Soc. 82*: 266–74.

CORBY, G. A., 1957: A Preliminary Study of Atmospheric Waves Using Radiosonde Data. *Quart. J. R. met. Soc. 83*: 49–60.

REID, D. G., 1952: Standing Waves. *Aust. met. Mag. 2*.

SCORER, R. S., 1949: *Quart. J. R. met. Soc. 75*: 41–56.

———, 1953: *Ibid. 79*: 70–83.

———, 1954: *Ibid. 80*: 417–28.

———, 1955: *Ibid. 81*: 340-50.

WALLINGTON, C. E., 1953: A Lee-wave Scale. *Quart. J. R. met. Soc. 79*: 545-7.

A NOTE ON TIDAL CIRCULATION IN PORT NICHOLSON, NEW ZEALAND

By J. W. Brodie, New Zealand Oceanographic Institute, Department of Scientific and Industrial Research, Wellington

(Received for publication, 19 August 1958)

Summary

Dye patch movements and other indicators demonstrate a complex zoned tidal stream flow into Wellington Harbour. In the harbour, the flood stream makes clockwise and the ebb runs anti-clockwise at rates approximating a quarter-knot. The boundaries between zones moving with different horizontal velocities are marked by slicks.

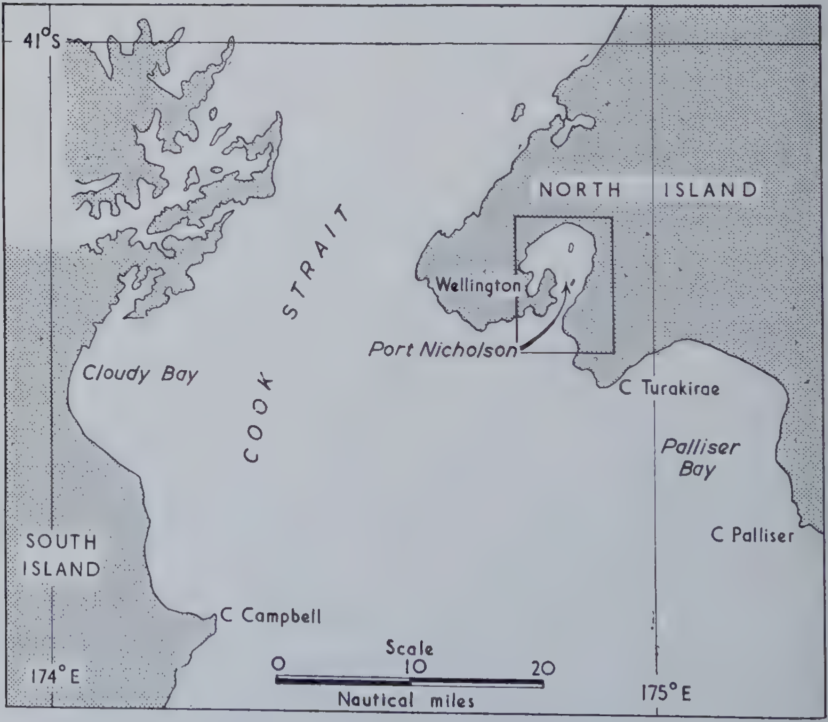

Fig. 1.—Port Nicholson and Cook Strait.

INTRODUCTION

Some simple methods of tide stream measurement have been tested in Port Nicholson (Wellington Harbour), a roughly equidimensional basin 30 square miles in area, with an average depth of 11 fathoms, connected by a channel 4 miles long, 1 to 2 miles wide, and 6 to 7 fathoms deep with the open waters of Cook Strait (Fig. 1). The harbour catchment has an area of approximately 280 square miles, and most of the drainage of this area is concentrated in the Hutt River which flows into the harbour at its north-eastern corner. The river's average flow is 1,000 cusecs, and maximum recorded flow approximately 70,000 cusecs (Mr H. E. Sladden, pers.comm.).

Observations were made of the movement of fluorescein dye patches, of discoloured water from the Hutt River and smaller streams and of small surface floats. Results of float observations carried out by the Hutt Valley Drainage Board were also made available. Temperature measurements were made and water samples for salinity collected. The data obtained give some information on the tidal stream pattern and hydrological conditions. Comments on the hydrological environment of the harbour as an ecological factor have been made by Maxwell (1956). Seasonal and other temperature variations have been described by Skerman (1958), and the results of bacteriological surveys have been presented by Johannesson and Martin (1955a, 1955b).

OBSERVATIONS

Drift Floats

Five wooden floats 12 in. by 1 in. by $\frac{1}{8}$ in. were released at high water at each of 24 stations in and around the harbour; at six stations five drift cards were also released. Cards were plastic-enclosed after the pattern described by Olson (1951). Eight cards and forty floats were recovered from the beaches next morning, mostly at high-water mark, and thus could have been afloat through the ebb and the overnight flood.

There was little wind during the day of release, but a strong north-west gale blew during the night and into the following day.

A month later, two similar releases were made around high water and low water. During the day, a south-easterly gale developed and continued for several days (Table 1).

The details of release stations and recoveries are shown in Fig. 2.

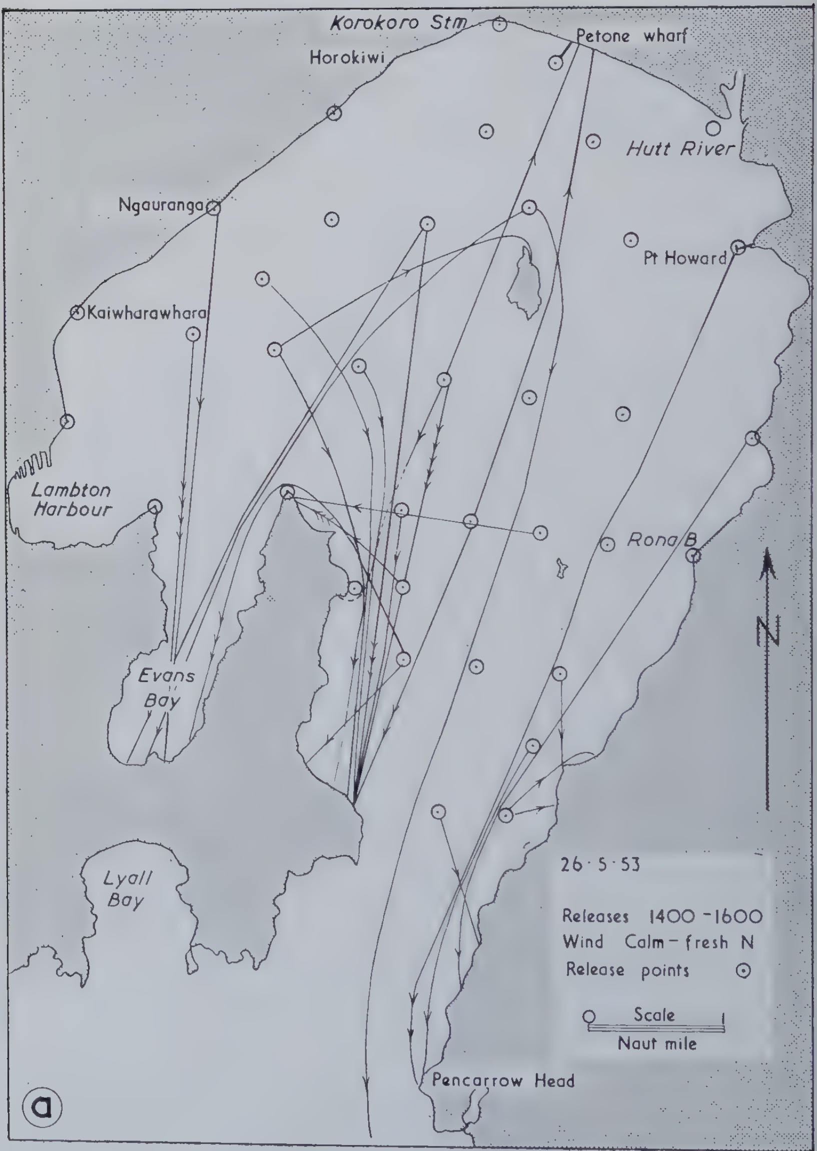

FIG. 2.—Release points and recoveries of drift floats: the number of arrows on each of the drift lines indicates the number of floats recovered.

(a) 26 May 1953, HW at 1500.

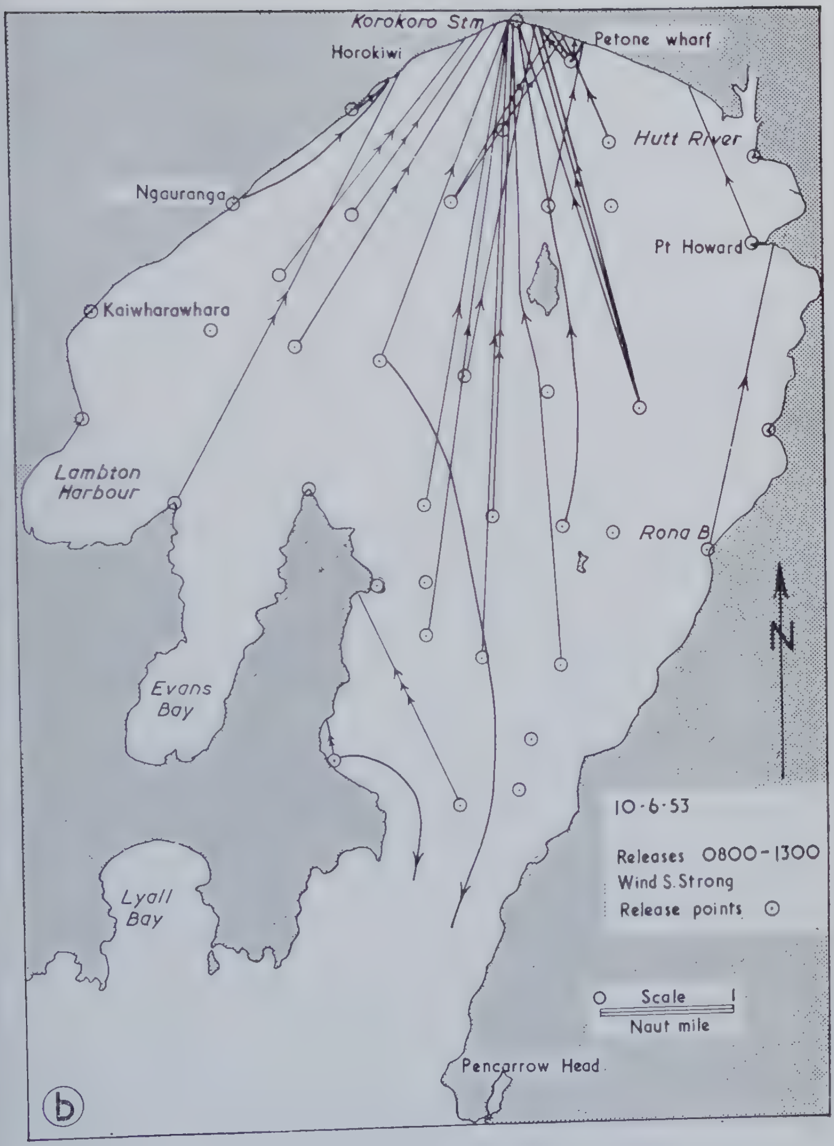

FIG. 2 (continued).

(b) 10 June 1953, LW at 0930.

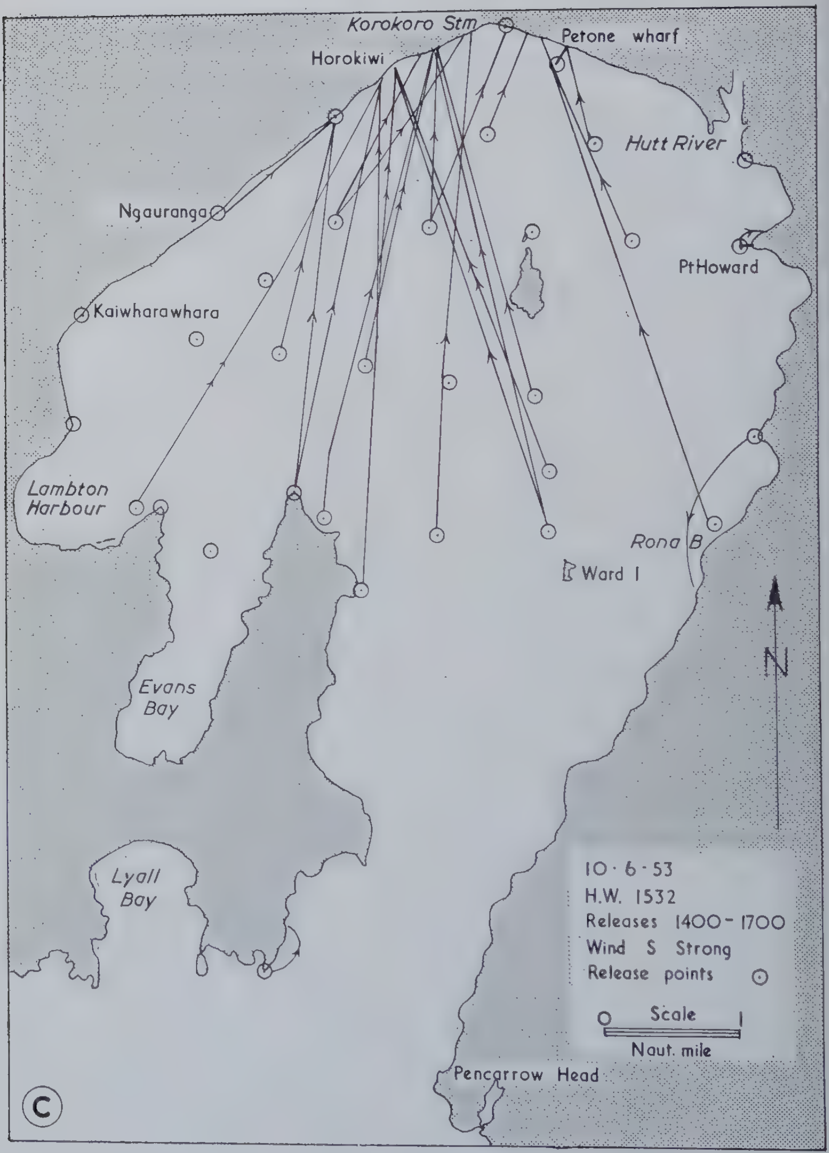

FIG. 2. (continued).
(c) 10 June 1953 (release at high water).

TABLE 1.—Velocity and Direction of Winds Recorded at the Meteorological Office, Kelburn, on 10 and 11 June 1953.

Time	Direction (°)	Velocity (knots)
10/6/53:		
0001	140	11
0300	140	8
0600	140	8
0900	140	18
1200	150	26
1500	140	27
1800	140	27
2100	150	22
2400	153	24
11/6/53		
0300	114	18
0600	150	20
0900	150	28
1200	153	22

Dye Patches

Four-ounce or eight-ounce packs of fluorescein dye were dropped at quarter-mile intervals along four lines across the central harbour, and the resulting patches observed from the air through the period half-flood to high water, and a second release, through the period high water to half-ebb. Within a few minutes the fluorescein spread to form a well-defined elongate patch two to three hundred feet long, which remained visible for about two hours. The results are shown in Fig. 3. Winds varied from calms to light airs during the observations.

Temperature and Salinity

Measurements of surface temperature were taken either by thermometer or by recording thermograph, and samples for salinity obtained on each of the preceding occasions. Subsurface temperatures along two profiles were recorded by bathythermograph. Thermograph records were also obtained from M.V. *Tanea* through the entrance and into Cook Strait coincident with one of the sets of harbour records. The plotted results are shown in Figs 4 and 5: the range of temperature and salinity encountered is given in Table 2.

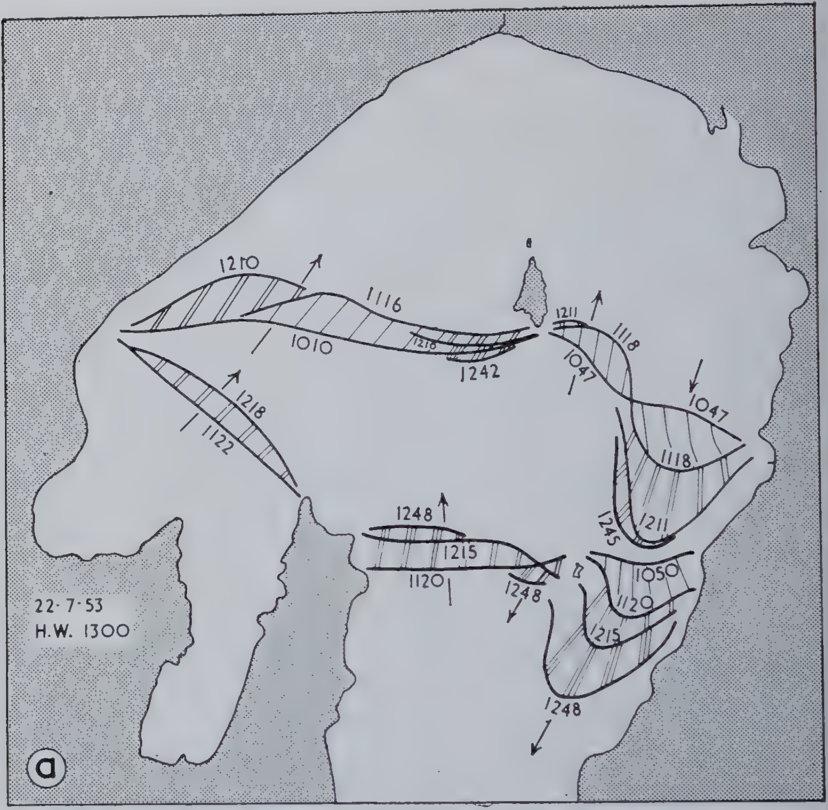

FIG. 3.—Movements of fluorescein dye patches, 22 July 1953: (a) Half-flood to high water (dye released 0930 h to 1130 h).

TABLE 2.

Date	Wind	Tide	Duration of measurements	Temp. (°F) Max.	Temp. (°F) Min.	Range	Salinity (‰) Max.	Salinity (‰) Min.	Salinity (‰) Av.
26/5/53	SE1	HW1500	1400–1600	54·0	51·5	2·5	33·31	22·28	32·8
10/6/53	S3	HW1532	1400–1700	54·0	52·0	2·0	33·77	23·50	33·0
10/6/53	S3	LW0930	0800–1300	53·5	50·5	3·0	33·64	31·35	32·9
22/7/53	NW1	LW0700	0930–1130	52·7	52·0	0·7	33·82	30·81	33·6
22/7/53	S1	HW1310	1200–1400	52·3	52·0	0·3	33·86	32·04	33·7

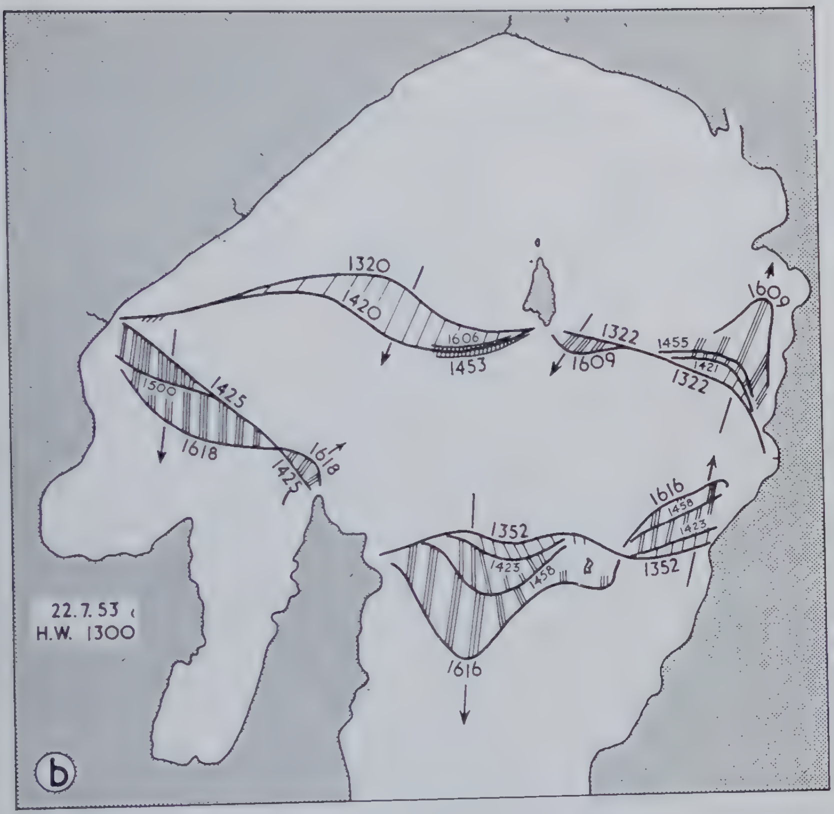

FIG. 3 (continued).

(b) High water to half-ebb (dye released 1200 h to 1400 h).

Fresh-water Outflows

The surface paths of fresh-water outflows when discoloured by sediment after rains were plotted over a period of years as opportunity offered. Records were made from Kelburn and from Beacon Hill. Typical patterns are shown in Fig. 6.

Current Floats

The Hutt Valley Drainage Board released some 280 floats at Tunnel Point, Inconstant Point, and off Pencarrow Head in the entrance to Port Nicholson. Half of these floats were ballasted submerged vanes with pole, float, and flag, designed to respond to movement 7 ft below

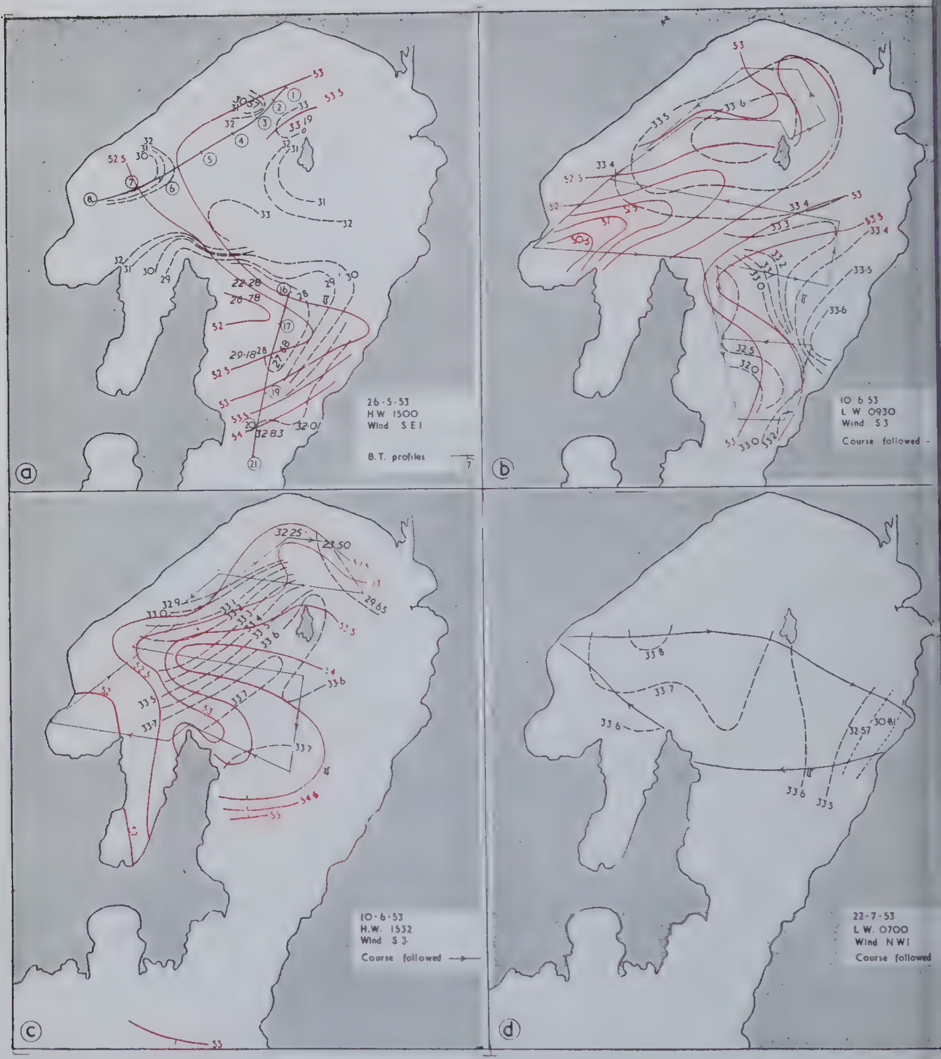

FIG. 4.—Temperature (° F) and salinity (‰) patterns: (a) 1400 h to 1600 h, 26 May 1953 (the course followed is not shown, but it is similar to that shown in Fig. 4 (b); (b) 0800 h to 1300 h, 10 June 1953; (c) 1400 h to 1700 h, 10 June 1953; (d) 0930 h to 1130 h, 22 July 1953 (water isothermal 52° F).

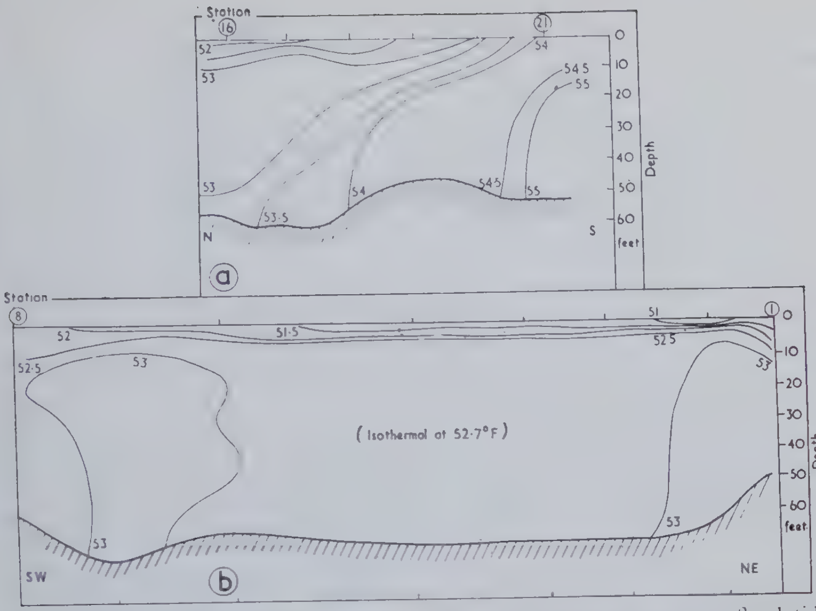

Fig. 5.—Subsurface temperature profiles (° F): (a) harbour entrance, flood tide, 1330 h to 1400 h, 26 May 1953; (b) inner harbour, flood tide, 0900 h to 1100 h, 26 May 1953.

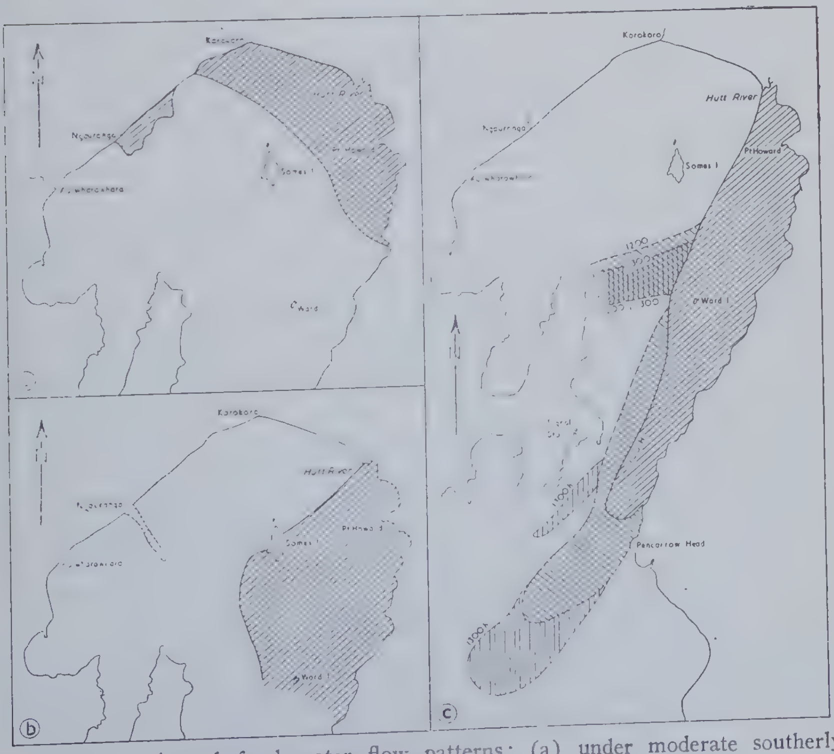

Fig. 6.—Discoloured fresh-water flow patterns: (a) under moderate southerly winds, 1600 h, 16 June 1953; (b) under light northerly winds, 1330 h, 6 June 1953; (c) under light northerly winds and ebb tide, 1100 h to 1300 h, 17 August 1954.

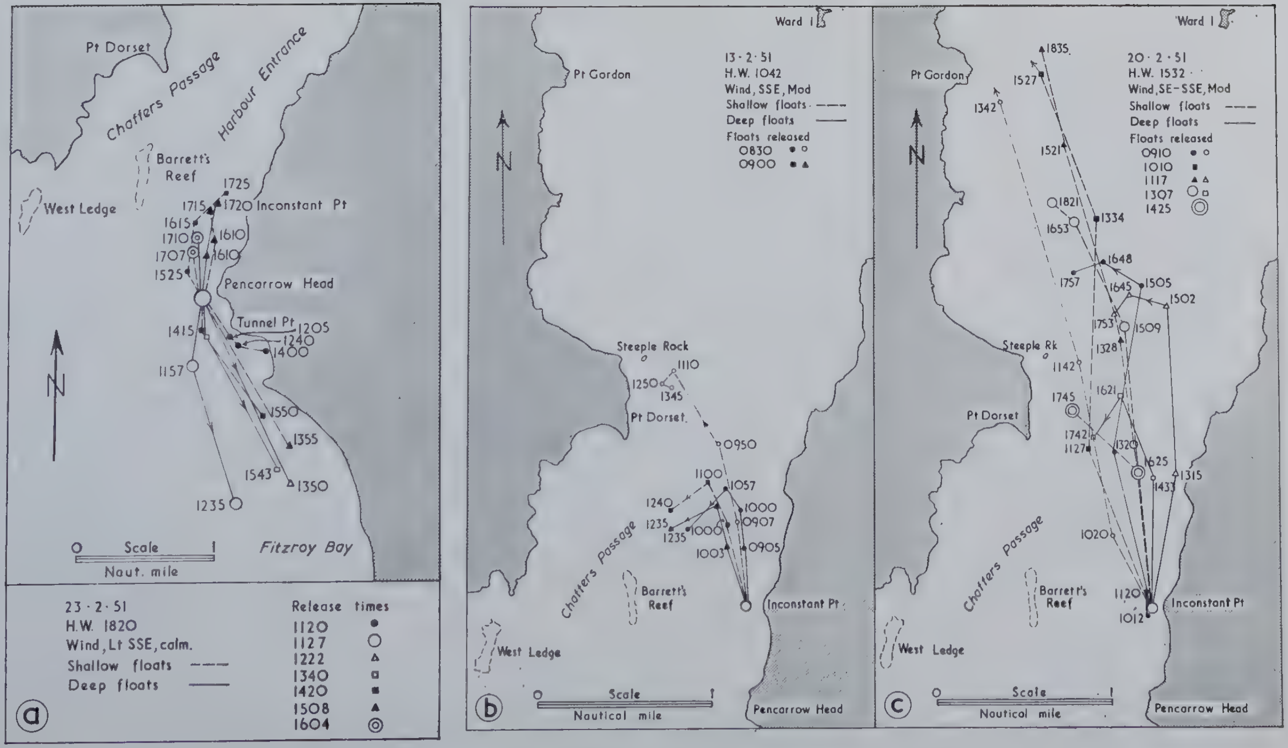

FIG. 7.—Current float movements at the harbour entrance.

the surface, the remaining floats (20 in. square flat board, ballasted and with pole and flag), to respond to surface movements. Floats were released hourly on days when the wind was less than 20 knots and were tracked from a launch.

Typical patterns of movement are shown in Fig. 7.

RESULTS

Drift Floats

Of the first drop of floats on 26 May 1953 (followed by strong north-westerly winds), 20% were recovered on the following morning, 35 having travelled south and only 2 to the north. One drift card of the 8 recovered was returned from Cape Turnagain on the East Coast of the North Island, 150 miles north of Wellington Harbour. Most of the floats and cards were found at high-water mark. These could have been afloat through the ebb and overnight flood.

From the two releases (370 floats) under southerly conditions on 10 June 1953, 22% of the floats were recovered from the beaches the following morning; 78 of these had travelled north and 1 south. More than half were concentrated on Petone Beach in the north-western corner of the harbour.

The course of the floats obviously depended principally on the wind direction, the floats moving directly before the wind (Table 1). However, the principal concentration of recoveries from the cards of the morning release of 10 June (which could have been affected by flood, ebb, and flood) was located 1½ miles east of those from the afternoon drop (affected only by ebb and flood). If this shift is due to the effect of a flood tide, then a clockwise movement of 1½ miles is indicated for this area during the flood stream. This gives a rate of one-quarter knot, consistent with other observations.

One drift card was not recovered until three weeks after release (and then from a regularly visited beach).

The results demonstrate the effectiveness of transport of floating material by strong winds, the possible persistence of the normal tidal stream pattern even under extreme winds, and the unsuitability of the wooden float for tidal stream observation.

Dye Patches

The plots of dye-patch movement show the tidal streams running at the surface in discrete zones. At late flood, water entering the harbour is moving north past Point Halswell and generally north-going at an average rate of one-quarter knot in the western half of the harbour and just to the east of Somes Island; at the same time there is a strong southwards flow (average rate half a knot) in the eastern portion of the harbour. The high salinities demonstrate that this is not merely a surface freshwater outflow from the Hutt River. The early ebb pattern shows a complete reversal of the flow directions.

In brief, under calm conditions, flood streams ran clockwise and ebb streams anti-clockwise in the harbour.

Detail of this zoning is shown in Fig. 8, where slicks separate adjacent zones, and in Fig. 9, where the frictionally tied inshore zone is separated by a slick from the moving off-shore zone; the fluorescein patch has taken up a similar form to the slick boundary.

Temperature and Salinity

Temperature and salinity observations to cover the harbour must be spread over a period of time unless a number of vessels are available. The present results are thus non-synoptic and confined to an indication of the range of values to be expected. All the observations were made in the mid-winter months; the tidal inflow from Cook Strait is warmer than the harbour water, and the vertical temperature section shows that

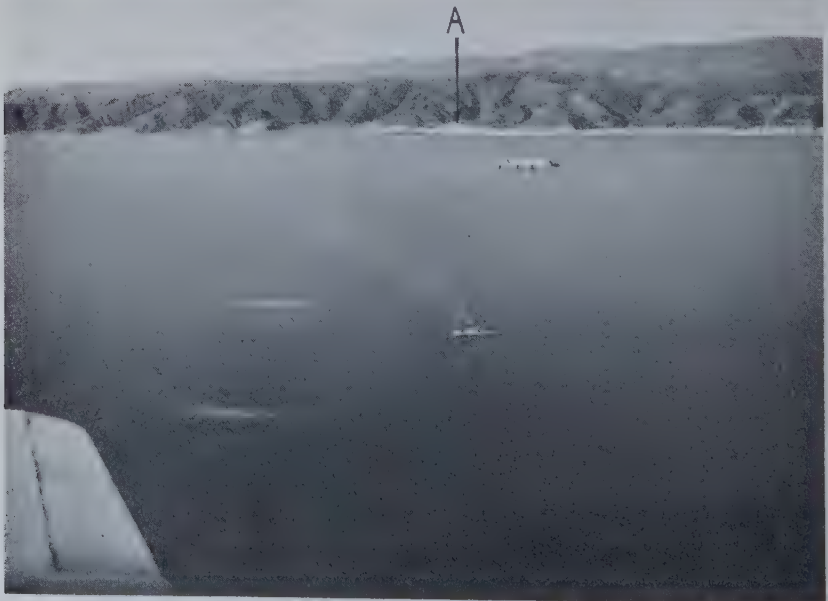

FIG. 8.—Differentially moving zones of surface water on the ebb tide. The dye patches were initially laid in a straight line from the left foreground towards point A. (1424 h on 22 July 1953).

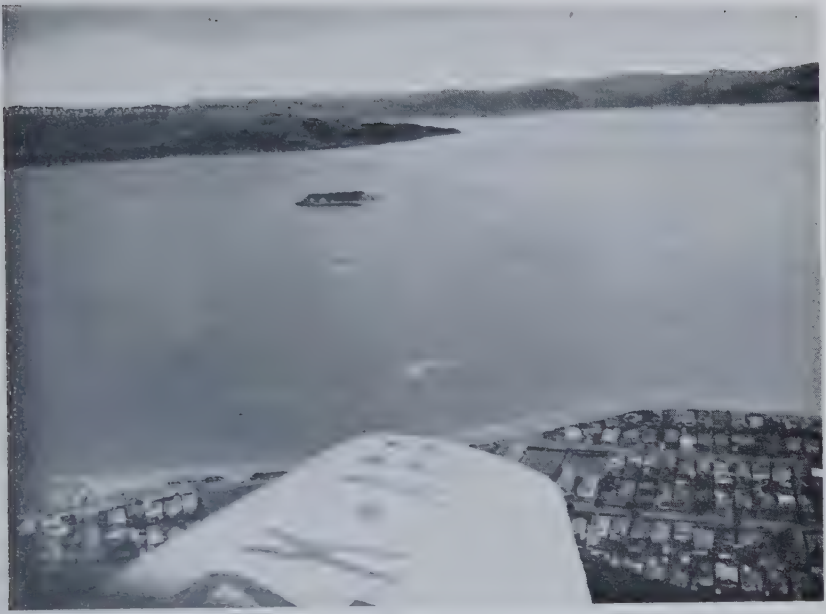

FIG. 9.—Dye patches 25 minutes after laying. Movement parallel to the slick is apparent. (1050 h on 22 July 1953).

it wedges its way forward into the harbour entrance (Fig. 5). The range of temperatures and salinities is shown in Table 2.

On 26 May 1953, on the flood and at high water, the inner harbour water was predominantly isothermal at 53° F under a cooler 51·5° F surface layer about 5 ft in depth. Warmer water lay outside the entrance, and a patch of low salinity (22·28‰ min.) and low temperature (52° F) water was located in the western side of the harbour entrance, apparently separated from its probable source in the Hutt River.

On 10 June 1953, for the ebb tide under a moderate southerly wind, salinities were mostly high (33·0‰) and temperature minima were found in Lambton Harbour and the western entrance.

On 22 July 1953, under almost calm conditions, the surface waters were near-isothermal at 52° F and near-isohaline at 33·7‰. Low salinities appeared both at low water and at high water along the eastern shore.

For all these occasions, some points of similarity can be detected between the isolines of temperature and salinity and the pattern of movement shown by the fluorescein patches on 22 July. The surface temperatures in particular suggest tongues of tidal flow. Fresh-water outflow from a number of points around the harbour shores produces a more varied distribution pattern for salinities.

Discoloured Water

During winter months, freshes in the Hutt River and Ngauranga Stream bring down large volumes of silt-laden water. The Ngauranga Stream outflow possesses a permanent marker in the shape of industrial effluents. The behaviour of the thin layer of fresh surface water under the influence of southerly or of north-westerly winds (the two commonest winds) can best be described in terms of the outflow of these two streams.

Under northerly (and north-westerly) winds, the Hutt River outflow is confined to a narrow zone down the eastern shore of the harbour. In winds of force 3, the zone is one mile wide under moderate flood conditions. The zone is further compressed in heavier winds. The Ngauranga Stream outflow under northerly conditions is a simple tapering south-east-pointing tongue 1 to 2 miles long and $\frac{1}{4}$ to 1 mile wide at the stream mouth. The outer portion of this tongue is deflected to the north on the flood and south on the ebb tide. The Korokoro stream develops a similar south-trending tongue.

In southerly winds, the typical placement of discoloured fresh water is across the northern end of the harbour. With prolonged outflow, the discoloured area extends south, its margin remaining parallel to the northern shore. The layer is extremely thin, and at the peak of the flood stream blue water has been seen to break through the brown overlying layer in a pattern of streaks.

A series of records was made on 12 June 1953 which typifies the progressive development of southerly conditions (Fig. 10). When the margin nears the south end of the harbour, in the lee of the land, the effect of wind is diminished and the margin extends farther south towards the sheltering headlands.

The Ngauranga stream outflow is compressed under southerly conditions, being only $\frac{1}{2}$ to 1 mile long, bunched around the stream mouth and pushed northward along the coast.

At the harbour entrance, the discoloured water usually extends to Pencarrow Head, and the sides of the channel and Chaffers Passage often remain clear under both southerly and northerly conditions.

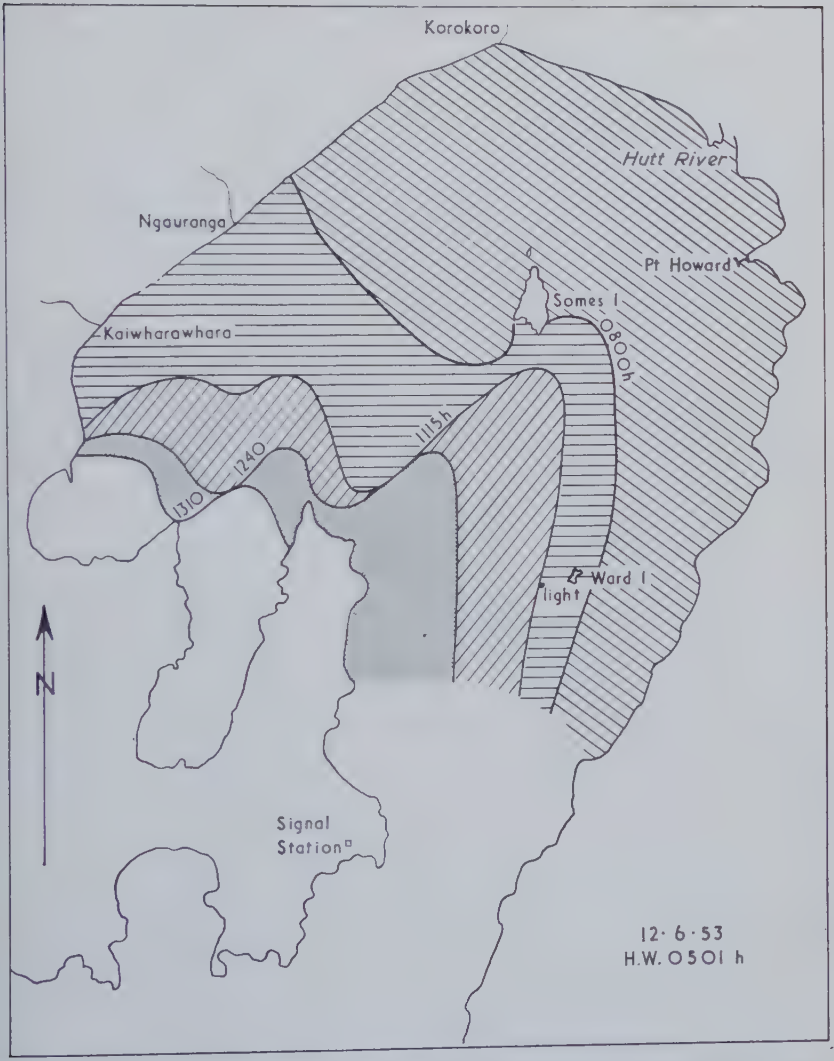

FIG. 10.—Successive positions of southward moving margin of discoloured freshwater outflow from Hutt River and lesser streams under light southerly conditions.

Current Floats

The floats indicated an average rate for the tidal streams near the harbour entrance, in the channel, and in Fitzroy Bay of half a knot. The time of turn of the flood or ebb stream in the channel approximately coincided with high water or low water at Wellington, and the flood stream turned 1 hour before high water at Wellington under strong north-north-west winds and the ebb turned before low water at Wellington under the influence of strong southerlies.

The deep floats (under both southerly and northerly winds) showed the stream turning at high water anti-clockwise across the channel in a semi-circle 2,000 ft in diameter. Lesser diameter clockwise gyrals were observed along the Pencarrow shore. The shallow floats did not execute complete turns, but tended to drift to the west. At low water the deep floats made clockwise turns across the Heads, anti-clockwise gyrals occurring along the shore.

Off Pencarrow Head, observations showed that the flood runs north-north-east into the channel and south-south-east into Fitzroy Bay; the ebb runs south just off the Heads and into Fitzroy Bay and to the west farther seaward across the Heads. All the Fitzroy Bay measurements were made under northerly conditions.

TIDAL STREAM PATTERN

All the stream observations from dye movements, current floats, and fresh-water outflows have been compounded in the generalized chart (Fig. 11). The dye movements indicate that the stream pattern is more complex than shown here and does in places include zonation in which half-mile-wide zones of water are moving differentially, separated by slicks. These were particularly pronounced on the day of observation, between Point Halswell and Rona Bay at the harbour end of the entrance channel.

For the periods of observation, little contradiction occurs when results are combined. At the harbour entrance, the flood stream inshore ran south-south-east into Fitzroy Bay and north-north-east into the entrance channel; between Point Halswell and Ward Island, the stream made north and generally held to a clockwise movement out of Lambton Harbour and along the western harbour shore; a pronounced southward surface flow was located along the eastern shore (this flow was not markedly less saline than the balance of harbour water). At the turn of the flood stream an anti-clockwise movement took place in the entrance channel, setting up lesser clockwise eddies along the eastern shore, and the movement of water inside the harbour reversed and flowed anti-clockwise.

The average rates of flow observed were approximately ½ knot in the constricted entrance channel and ¼ knot inside the harbour proper. (Detailed observations are also reported on Chart N.Z. 50.)

There is slight evidence for wedging of incoming salt water under harbour water with the flood stream, but the degree of underthrusting is small, the difference in density being small. Only slight development

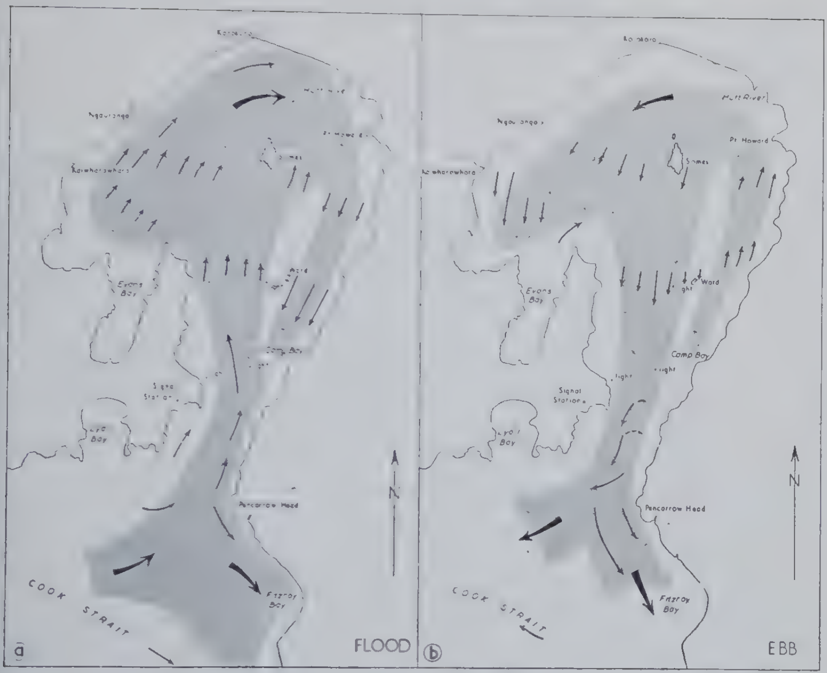

FIG. 11.—Generalized tidal stream pattern in Wellington Harbour: (a) flood; (b) ebb.

of normal estuarine circulation can be expected. The effect of friction in retarding movement along the shoreline is well shown by the dye movements. On a smaller scale, a narrow (20 to 30 ft) stationary zone has been observed along the shoreline, separated by a slick from an offshore zone moving at ½ to 1 knot. That the slick patterns observed are related to horizontal water movements is shown by the fact that fluorescein patches (which elongate in the direction of movement) have been observed to parallel some sinuous slicks (Fig. 9). Abrupt though small temperature changes are met with on crossing from one zone of flow to the next. These may simply indicate different degrees of mixing of the upper water layers at different rates of flow.

TECHNIQUES

The drift float and surface fresh-water movements are of value in indicating the probable pattern of dispersal of floating material within the harbour under the effect of wind. The most effective tidal stream indicators are dye patches, mainly because the method readily permits synoptic observations, and the deep-current floats which are independent of the effects of wind on the surface layers. This last method is, however, expensive of time and effort.

ACKNOWLEDGEMENTS

Thanks are due to many members of the staff of Geophysics Division, D.S.I.R., for assistance in the field; to Mr D. M. Garner and Mr N. M. Ridgway for carrying out observations on the harbour and assistance with plotting results; to the Hutt Valley Drainage Board, Mr H. Reynolds Bach, and Mr H. M. Cotton for the use of float data; to the Wharf Police and Mr K. Weir for the use of launches; to Mr E. J. Thornley and Mr N. S. Beatus for photography and observations from the air; and to the Harbourmaster, Captain D. Todd, and the Signal Station staff for observations of flood waters at the harbour entrance.

REFERENCES

JOHANNESSON, K. J.; MARTIN, RAIMONNE E., 1955a: The Bacteriological Survey of Wellington Harbour—II. *N.Z. J. Sci. Tech. B 37 (2)*: 224–42.

———, 1955b: The Bacteriological Survey of Wellington Harbour—III. *Ibid., B 37 (4)*: 445–54.

MAXWELL, BRIAN E., 1956: Hydrobiological Observations for Wellington Harbour. *Trans. roy. Soc. N.Z., 83 (3)*: 493–503.

OLSON, F. C. W., 1951: A Plastic Envelope Substitute for Drift Bottles. *J. Mar. Res. 10 (2)*: 190–3.

SKERMAN, T. M., 1958: Seasonal Variations in Sea-water Surface Temperatures Within New Zealand Harbours. *N.Z. J. Geol. Geohpys. 1 (1)*: 197-218.

THE WAIRAKEI HYDROTHERMAL FIELD UNDER EXPLOITATION

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Summary

Heat flow through drillholes in the Wairakei hydrothermal field now equals the pre-existing natural heat escape, while this heat escape itself is little diminished. The total heat flow at surface has thus been doubled, and the source of this increase has an important bearing on the life of the field under exploitation.

The drillholes tap the Waiora aquifer, in which the low density of the hot water gives rise to pseudo-artesian pressure, here designated thermo-artesian. There has been a general decline in this pressure, consequently cold water must be encroaching on the field, although drillhole temperatures show little evidence of this. Some of the increased heat flow must therefore come from heat stored in the rocks and ground water, and this is a wasting asset.

The history of Wairakei's hot springs, and the very uniform physical and chemical conditions in the aquifer, indicate a long-established state of equilibrium. This is now being destroyed by exploitation, revealing at least one point, on the Waiora Fault, at which hot water is fed into the aquifer. The feed channel is found to have so low an impedance that it may be possible to increase the rate of feed, by suitably placed holes, without excessive drawdown or exhaustion of storage. A limit to this increase will be set by the danger of blockage by calcite deposits; blockages can be cleared from the drillholes, but not from the feed channel.

If the heat supply to the aquifer is thus increased, adjacent sections of the Waiora Fault may then channel cold water into the field, and thus tend to curtail the utilization of stored heat.

INTRODUCTION

The natural heat escape from the whole of the Wairakei hydrothermal field, prior to exploitation, has been given as $1 \cdot 5 \times 10^5$ kcal/sec, or $2 \cdot 1 \times 10^9$ BThU/hr (Gregg, 1958: Table 3, sub-sheet N94/4; heat flow referred to 0° C). The author has pointed out in a previous paper (Studt, 1957) that there has been a substantial rise in surface heat flow as a result of exploitation; in fact, between the winters of 1955 and 1958, the mean heat output from drillholes has almost equalled the pre-existing natural heat escape. During this period, the natural heat escape itself has diminished little; in Geyser Valley, the decrease is of the order of 10%, but elsewhere there are indications that the flow has actually risen (Mr G. E. K. Thompson, pers.comm.).

The peak drillhole output to date has been $2 \cdot 2 \times 10^5$ kcal/sec ($3 \cdot 1 \times 10^9$ BThU/hr) and it is hoped ultimately to achieve more than twice this figure.

This paper discusses the source of the increased heat flow: whether it involves the withdrawal of heat which has been stored up in the rocks and the ground water during the life of the hydrothermal system,

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or whether exploitation may induce increased heat supply from below into the aquifer that is tapped by the drillholes. The solution to this problem is important economically, because it will determine the life expectancy of the Wairakei field under exploitation; but it is also of scientific interest, since it throws new light on the hydrology of this field.

The operations at Wairakei have been described by Grange (1955) and Smith (1958). A plan of the Wairakei area appears in Fig. 1, the location of drillholes and surface hydrothermal features being shown. Figure 2 shows a vertical section through the field, based on that of Grindley (1957, p. 120).

The term hydrothermal is used in this paper in the sense defined by White (1957): "of or pertaining to any water that is appreciably warmer . . . than the surrounding environment", without any magmatic connotation. The author is in agreement with White's reasons for this

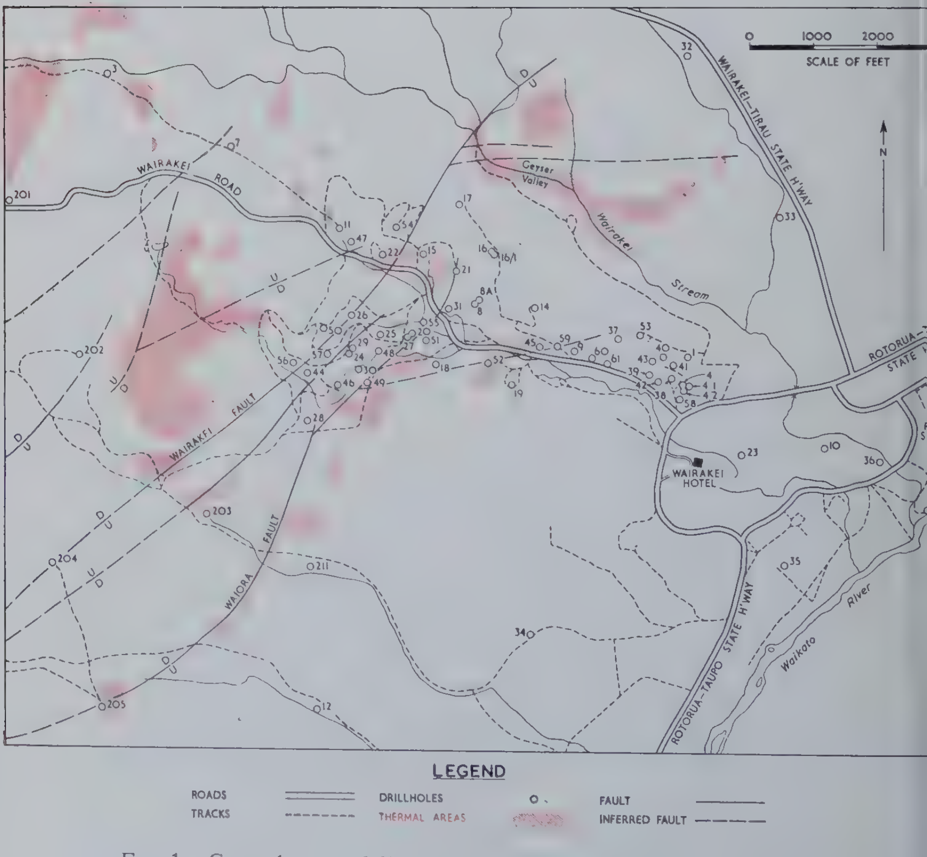

Fig. 1.—General map of Wairakei, showing locations of drillholes and surface hydrothermal areas.

usage. The term geothermal has a different meaning: "pertaining to the heat of the earth" (e.g., geothermal gradient, which is found in "cold" as well as in "thermal" areas). Its use as a synonym for hydrothermal is confusing, and should be avoided.

SIGNIFICANCE OF NATURAL HEAT ESCAPE

It will be shown below that heat is being withdrawn from storage at Wairakei, and it will also be suggested that the heat supply from below to the hot aquifer may be increased. If hydrothermal energy can be stored up and drawn upon in this way, then it follows that the natural heat escape is not necessarily a sure guide to the power potential of the field. In a province which is active both seismically and volcanically, there is no justification for assuming constancy of conditions for any length of time. Might not the present be a period of accumulating or dwindling heat storage? Might not the heat supply to the aquifer be much higher or lower than the heat escape at surface?

Banwell (1955, p. 61) has calculated that the heat stored within 3,000 ft of surface at Wairakei is $3 \cdot 4 \times 10^6$ cal/sq.cm. (referred to 100° C). This is an over-estimate, for Banwell assumed 300° C as the maximum temperature, whereas it has proved to be little higher than 250° C. Using this figure, however, it appears that the heat stored in five square miles of the Wairakei field would suffice to maintain the natural heat escape for one hundred years. Equally, it would take a hundred years for the same heat flow to build up the present storage. The history of Wairakei extends back over a hundred years without any known evidence for important changes in the hot springs, so that there cannot have been a heat supply from below 3,000 ft more than sufficient to maintain the heat escape and at the same time to build up storage to its present level. That is to say, the mean heat supply cannot have been more than twice the present natural heat escape. Over shorter periods, the actual supply could have been much higher, but such a change would have become manifest in the hot springs, for the increased heat supply is unlikely to have been matched by a proportionate increase in the cold-water influx, so that steam would have grown much more widespread (Studt, 1957).

On the other hand, the mean heat supply cannot have been much lower than the natural heat escape, for that would involve the hot springs being supplied from storage, and storage in the past cannot have been much greater than at present, because the hydrothermal alteration pattern shows no widespread evidence of higher temperatures than are found at present (Mr A. Steiner, pers.comm.).

It is believed, therefore, that the heat supply from below 3,000 ft depth is unlikely to differ from the natural heat escape at surface by a factor as high as 2; in fact, the disparity is probably very much smaller than this. Exploitation, on the other hand, has already doubled the heat escape, and the source of this extra heat therefore presents a very real problem.

WAIRAKEI HYDROLOGY

In examining this problem, it must be borne in mind that Wairakei hydrology is complex. At surface, there is catchment in the west, with runoff and percolation through the Wairakei Breccias (Fig. 2) directed eastward toward the Waikato River. Where temperatures are high, and densities therefore low, a greater depth of water is required to balance the cold water in the surrounding country; this results in a raised water table and hot springs. In the high country to the west is a zone in which water, though hot, does not reach surface; steam rises from the water table, giving perched pools and mudpots, or steaming ground.

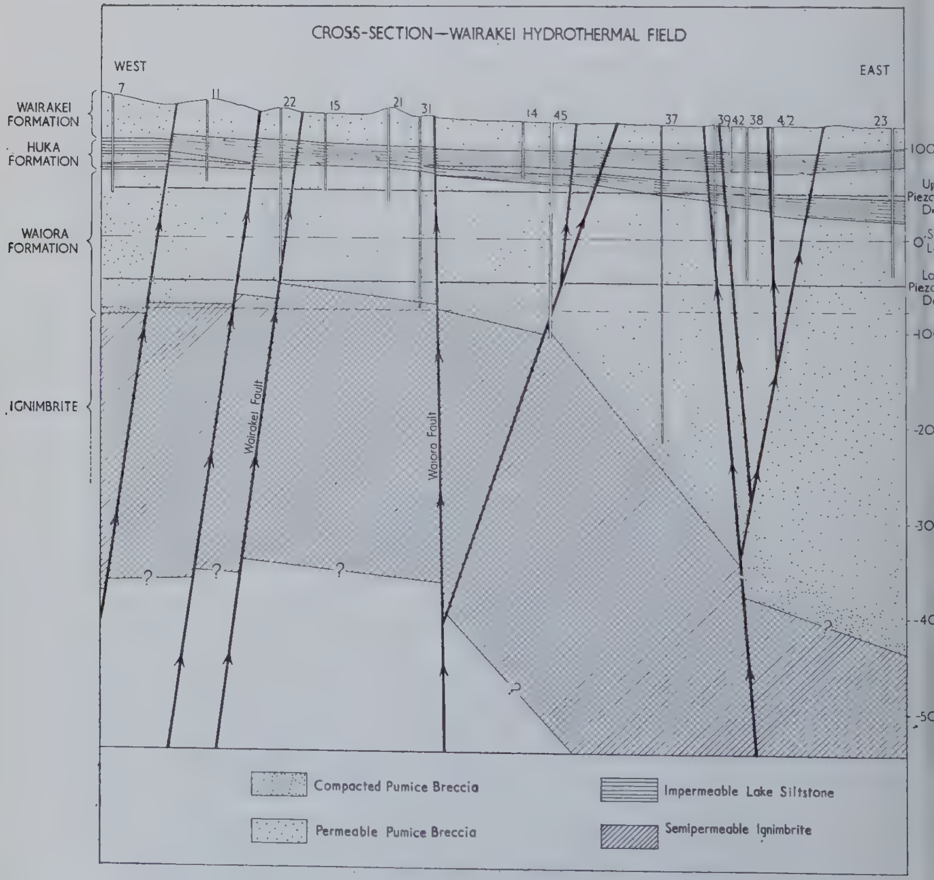

FIG. 2.—Cross-section of the Wairakei field (after Grindley).

The Confining Beds

The above system is confined to the top two or three hundred feet of the rock sequence and has no direct bearing on conditions at greater depth, for it is underlain by the Huka Mudstones, which provide a relatively impermeable barrier to the upward movement of hot water. The mudstones undoubtedly account for the large extent of the Wairakei field, since the hot water is forced to migrate laterally beneath these beds before it can escape to surface. The escape paths are provided by a number of tension faults, mostly striking north-north-east, along which many surface hydrothermal features are aligned.

The long life and constancy of the heat flow may also be attributed to the influence of the mudstones. In fact, there are good reasons for believing that, without such an impeding layer, the hydrothermal system as we know it could not exist; the energy would be dissipated by eruption.

The Waiora Aquifer

Beneath the mudstones are the permeable Waiora Breccias, which constitute the main hot aquifer, varying in thickness from about 1,200 ft in the west to more than 2,600 ft in the east of the field. Here, the low density of the hot water produces a pseudo-artesian pressure, so that drillholes tapping the aquifer discharge spontaneously, or stand under pressure when shut in. The aquifer is not artesian in the conventional sense, for the water level may be as much as 200 ft below surface in drillholes that have been cooled by circulating cold water; pressure develops only when temperatures recover. This pressure, here referred to as "thermo-artesian" pressure, is entirely due to high temperature, not only in the aquifer itself, but also in the overlying beds, for this maintains a low density in the upper part of the water column.

Lower Formations

The Waiora Formation is underlain by the Wairakei Ignimbrite, which is generally taken to be the bottom of the aquifer. However, frequent loss of drilling fluid has shown that this rock, although massive, has some degree of permeability afforded by joints and fault planes, so that its upper layers at least should be regarded as part of the aquifer. Even in the tuffs and breccias at the bottom of the Waiora Formation, movement of water appears to be predominantly along fault planes, for the productivity of drillholes depends on the degree of fragmentation of the rocks encountered. For this reason, most of the deeper holes have been drilled to intersect faults.

The Wairakei Ignimbrite has a thickness of more than 2,000 ft at hole 48; probably there are a number of successive sheets in this range, and minor sedimentary layers may be interbedded with them. What lies beneath the formation is not yet known. On the Kaingaroa Plateau, to the east, ignimbrite is known to lie directly on the Mesozoic basement, but elsewhere on the Waikato River it overlies earlier tuffs and breccias, which at Wairakei might constitute deeper aquifers.

Rhyolite appears above the ignimbrite in the south and south-west, progressively cutting out the Waiora aquifer from below. Like the ignimbrite, however, this rock is permeable in its upper layers.

TEMPERATURE AND PRESSURE DISTRIBUTION

Temperature

Banwell (1957) has dealt in some detail with the temperature distribution. Generally speaking, there is a rapid increase in temperature with depth, down to the base of the confining mudstone. At this point, temperatures are commonly close to, or above, the boiling-point (about 200° C) corresponding to the theoretical hydrostatic pressure for this depth below the water table. Actual pressures are higher than this, and free steam, though present, is not as a rule abundant. Through the Waiora aquifer, the temperature gradient is much reduced, reaching 250° C at about 1,500 ft depth. Below about 2,000 ft, the gradient is either very small or negative. Temperature peaks within the aquifer suggest that minor mudstone layers locally influence vertical movement of water, but there is no indication of discontinuities affecting the lateral movement through the aquifer, except where the rhyolite occurs.

Withdrawal of heat from storage will take the form of movement of hot water into the drillholes, its place being taken by colder water from the surrounding country. Because there has been little decline in drillhole temperatures, it has sometimes been assumed that this movement is not taking place. However, this assumption is unjustified. Wilson (1955) drew attention to the uniform concentration of certain chemicals in the water of the Waiora aquifer. He concluded that, if there is mixing of cold ground water into the hot fluids, this must take place below the depth of the drillholes. It will be shown here that little penetration of cold water is possible at present, except in the deeper levels, where temperature data are scarce; at these deeper levels, however, inward movement of cold water must be taking place.

Pressure

This problem is essentially hydrological, and, since there is no evidence of large bodies of steam, the hydrological techniques used in cold areas should be applicable at Wairakei, so long as due regard is paid to temperature effects. Cold water can penetrate into the hydrothermal system only where the hydrostatic head in the cold country is greater than that in the hot.

The hydrostatic head at any point in a cold aquifer is given by the height of the static water level above that point, in a hole drilled and cased down to that point. The piezometric surface, built up by interpolation between such water levels, is a convenient means of depicting the pressure distribution and direction of flow in the aquifer. At Wairakei, the high temperatures upset this simple relation, and it is necessary to compute the water level that would be found if a similar mass of cold water replaced all hot water above the datum for which the head is required. Details of this simple computation are given in the appendix to this paper. Owing to complications introduced when free steam is present in the water column (also described in the appendix), individual computations may be in error by 20 ft or more, and some results have to be rejected altogether. Nevertheless, many holes give quite consistent results.

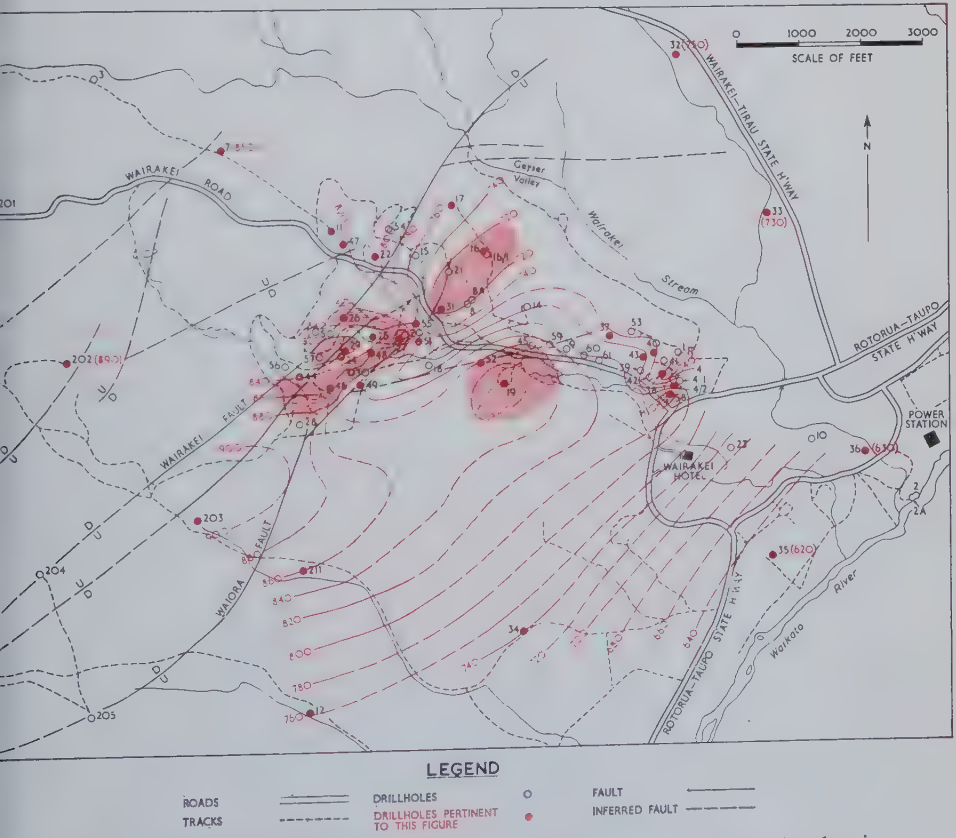

FIG. 3.—Upper piezometric surface in 1958, contoured at 20 ft intervals, showing the distribution of hydrostatic head in feet of cold water at the upper datum, 500 ft above sea-level.

Once the temperatures in a hole have reached equilibrium with those in the surrounding strata, and so long as there is no free steam and no very rapid vertical movement of water, the pressures in the hole should be indicative of those in the aquifer. This applies, of course, only to holes that are cased at least down into the confining mudstones. Since practically all the Wairakei holes come into this category, it is possible to construct piezometric surfaces to indicate the probable flow pattern at various levels in the Waiora aquifer. Figures 3 and 4 show two such surfaces, related to datum levels respectively 500 ft above and below sea-level. They are defined by contours at 20 ft intervals and show the distribution of hydrostatic head, expressed in feet of cold water.

THE FLOW PATTERN

Figure 3 shows that there is a general pressure gradient directed from west to east. The general movement of water through the Waiora aquifer at the upper datum level must therefore be in the same direction as in the overlying beds, with recharge in the west and discharge in the east. No Waiora outcrops are known in the vicinity of Wairakei, and recharge, like discharge, probably takes place along fault planes.

Superimposed upon the general gradient is the detail due to geology, to high temperatures, and to the effects of exploitation. There are high-head zones centred around holes 19, 20, and 203, and the hot water must flow outward from these zones; in most parts of the field, in fact, the pressure gradients are directed outward, and cold-water intrusion is impossible at this upper datum. There are, however, low-head zones, especially that around hole 31, in which cold-water salients may develop, but as yet there is no instance of declining temperature at this level.

Figure 4 is less complete, since some of the holes end well above the lower datum, but the pattern is very similar. Here, however, the outlying holes 32 and 33, both of which are cold, have higher pressures than holes in the centre of the field. At this level, therefore, water must move inward from the cold country toward the centre of the field, so long as there are permeable paths for it to follow, and the negative temperature gradients in the lower sections of many of the holes show that such paths do exist. Since in the west this datum coincides with the top of the ignimbrite, it must be accepted that cold water may advance through this formation; the decrease in hydrothermal alteration with depth in the ignimbrite is further evidence of this.

Even holes 12 and 34, which are warmer than 32 and 33, but not as hot as holes in the centre of the field, have higher pressures than some of the latter. It is estimated that, 500 ft farther down, pressure in hole 34 would equal the highest in the centre of the field, but at this level hole 34 is well into rhyolite.

A remarkable feature of Banwell's (1957) isotherm profiles is the contrast between the sharp boundaries of the Wairakei field in the north and east sectors with the rather remote and indistinct boundaries in

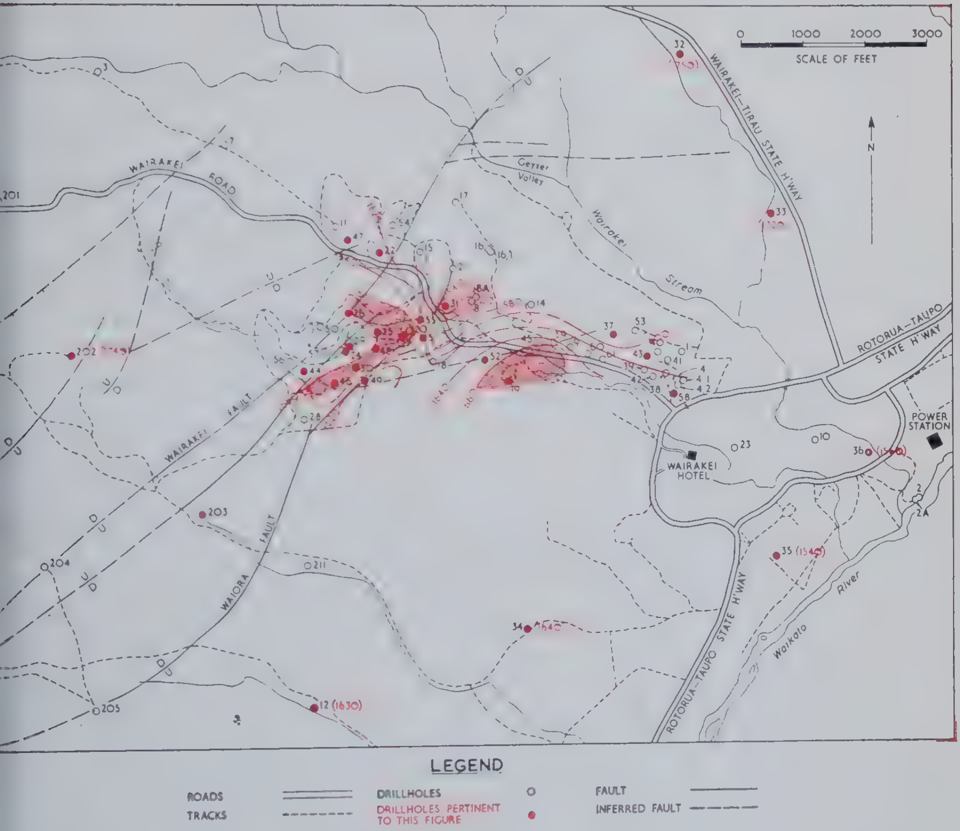

FIG. 4.—Lower piezometric surface, 1958. Datum 500 ft below sea-level.

the south and west. This may well be due to the fact that in the south and west the cold-water paths are in rhyolite and ignimbrite, where the permeability is lower than in the breccias of the opposite sectors, permitting less cold water to penetrate into the system.

Hole 202 has higher pressure than holes in the centre of the field, even at the upper datum. This is probably due to its location nearer to the recharge end of the aquifer, but, since its temperatures are high, this may mark a further active centre. However, this is of little import; owing to the fact that the ground surface rises more rapidly westward than does the piezometric surface, there is no thermo-artesian pressure at this hole. In June, 1958, the water level was 550 ft below the wellhead, with a wellhead pressure of 160 lb per sq.in. gauge. On release of this pressure, it is unlikely that the water level would rise much above 100 ft below the surface. A discharge might be started by airlift, for boiling would accompany the initial overflow, but it would probably be rather small and unreliable.

In addition to 202, a number of exploratory holes have shown that there is a large accumulation of heat in the western sector of the field. Lack of thermo-artesian pressure may make it uneconomic to tap this directly, but it will undoubtedly contribute to the output of drillholes farther east as this hot water moves eastward into the production area. This explains the relatively high pressures and satisfactory output of holes 26 and 44, which draw upon this flow, whereas holes 31, 51, and 49, being farther downstream, are forced to draw on less favourable resources to the south.

Effects of Exploitation

Changes in the Flow Pattern

Influx of cold water at the lower levels does not necessarily imply withdrawal of stored heat. Even in the absence of exploitation, the supply of heat to the bottom of an aquifer would set up convective

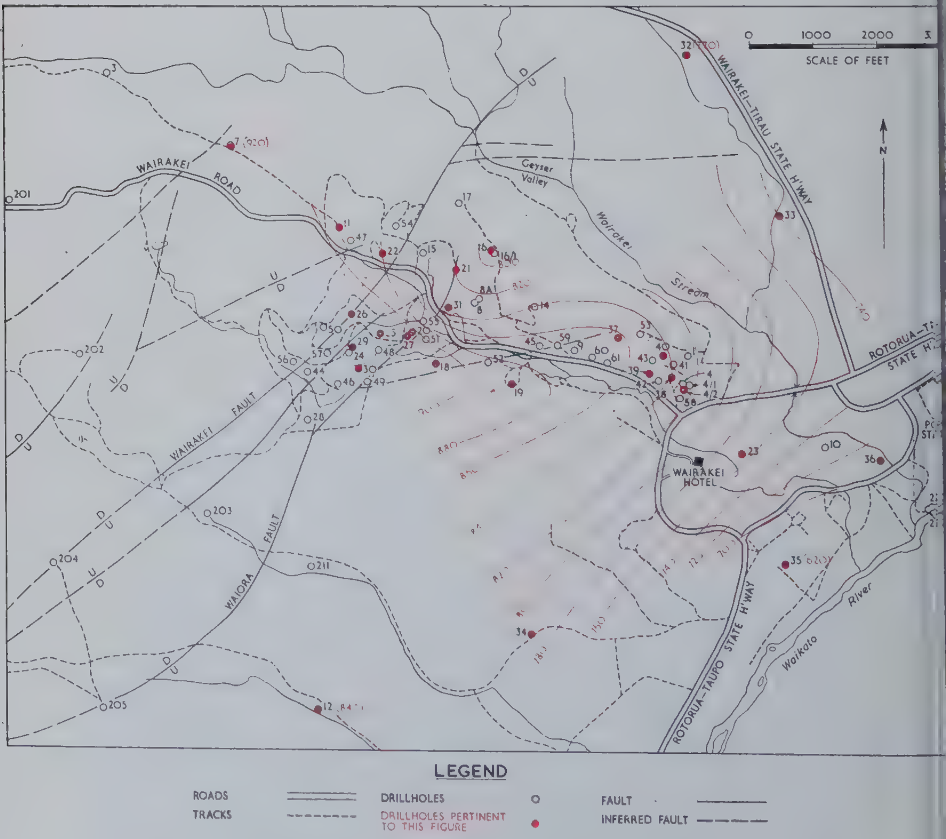

Fig. 5.—Upper piezometric surface, 1955. Datum 500 ft above sea-level.

circulation (Wooding, 1957; Studt, 1957), with outward movement of hot water at the top and influx of cold water at the bottom. It is generally agreed (Wilson, 1955: p. 27; Banwell, 1955: p. 47) that cold ground water does mix with the hot fluids as they rise toward the surface.

Changes have occurred in the piezometric surfaces, however, and there is little doubt that these are the result of exploitation. They are shown by a comparison of Figs 3 and 4 with Figs 5 and 6, which show the same two surfaces three years earlier. The more gentle relief of the earlier surfaces is due in part to the paucity of data at that time, but, as will be seen, there is reason to believe that the pattern was indeed smoother than it is now. The changes at the upper datum are contoured

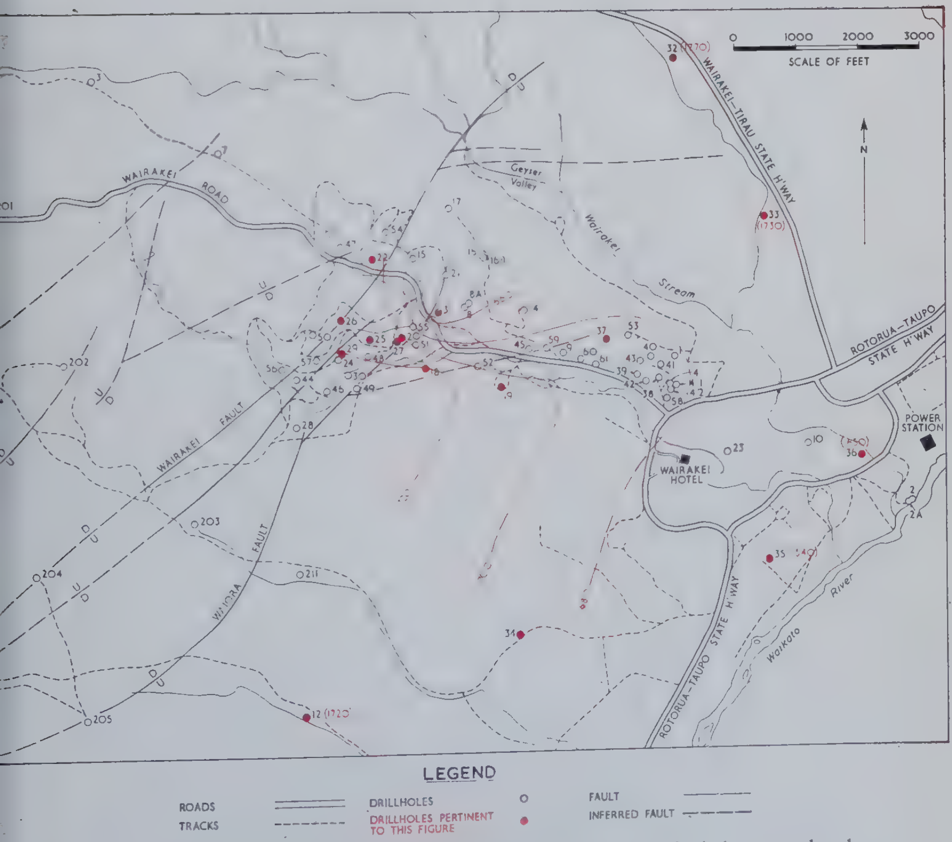

Fig. 6.—Lower piezometric surface, 1955. Datum 500 ft below sea-level.

in Fig. 7, but it must be remembered that, because some of the changes are not great by comparison with probable errors in the surfaces themselves, the low-relief detail of this figure has little significance. Changes at the lower datum are almost identical and are not shown; actual variations of head in some holes are shown in Fig. 8.

It is clear from the figures that there has been a general decline in pressure over much of the aquifer. This has been greatest in the most closely drilled areas; at outlying holes it has been small. It follows that outward flow of hot water at the upper levels must have been slowed, and inward flow of cold water at the lower levels accelerated, since exploitation began. There has thus been a net inward flow, and therefore extraction of stored heat is unquestionably taking place. This is not yet evident in the drillholes because the cold-water invasion comes from below, and not through the upper part of the aquifer.

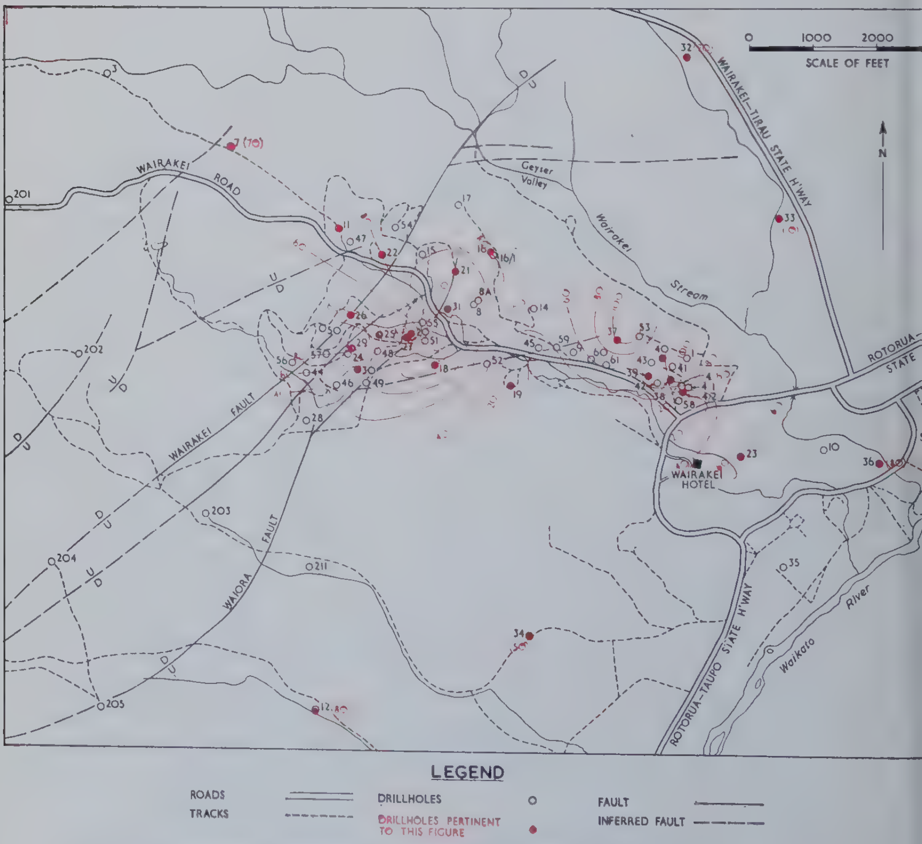

FIG. 7—Piezometric changes, 1955–58. Datum 500 ft above sea-level. The changes everywhere represent loss of hydrostatic head since exploitation began.

Loss of head in Wairakei drillholes is not as serious as in holes tapping a normal artesian aquifer, for discharge can be induced even though the water level is well below surface in the open hole. Nevertheless, output will deteriorate; some holes may cease to give economic discharge, and others will be downgraded from high to intermediate pressure (200 to 70 lb per sq.in.). Reference to curves given by Smith (1958) shows that a loss of 100 ft of head at hole 27 would cause 20% loss of steam under high-pressure operating conditions. This hole has about 200 ft of thermo-artesian head; most holes operate with much less, 60 to 80 ft being more representative at the present time, but many have already lost a similar amount of head.

Cause of Decline in Pressure

This loss of head at Wairakei is similar to that which occurs in any aquifer when water is pumped from it, but in a hot aquifer such as the Waiora the effects are twofold. Extraction causes the usual drawdown, or loss of pressure, but it also causes a decline in temperature which will, through associated density and viscosity changes, accentuate the drawdown. For instance, a change in temperature from 250° to 240° C throughout 1,000 ft depth of ignimbrite would produce a loss of 15 ft of head in the drillholes above; a 40° C fall over the same depth, or a 10° C fall over 4,000 ft, would be required to give the 60 ft loss of head experienced at a number of holes. Neither alternative seems appropriate; if the withdrawal of hot water had been sufficiently rapid to produce a big temperature drop in a large volume of ignimbrite, it seems likely that by now the drillhole temperatures would show some sign of this.

From the immediate economic standpoint, it is immaterial whether the loss of head is due to simple drawdown or to falling temperature, for in either case it results in loss of output. But it is important from the long-term standpoint, because drawdown simply limits the rate of exploitation, whereas falling temperatures limit also the life of that part of the output which is drawn from storage. The two are, of course, complementary, but drawdown must be present before cold water can be drawn into the system. This is the more important factor in the early stages, therefore; temperature effects will come later. The rapidity with which the first stage gives place to the second will depend on the permeability of the aquifer; high permeability would result in little initial drawdown and rapid penetration of cold water.

Through most of the Waiora aquifer at the present time, it seems likely that simple drawdown is still the dominant factor, but in certain areas where the loss of head is most marked there has probably been cold-water penetration along permeable paths. The only evidence to substantiate this is in holes 24, 25, and 29, whose deepest sections are now 10° to 20° C colder than in some of the earliest measurements.

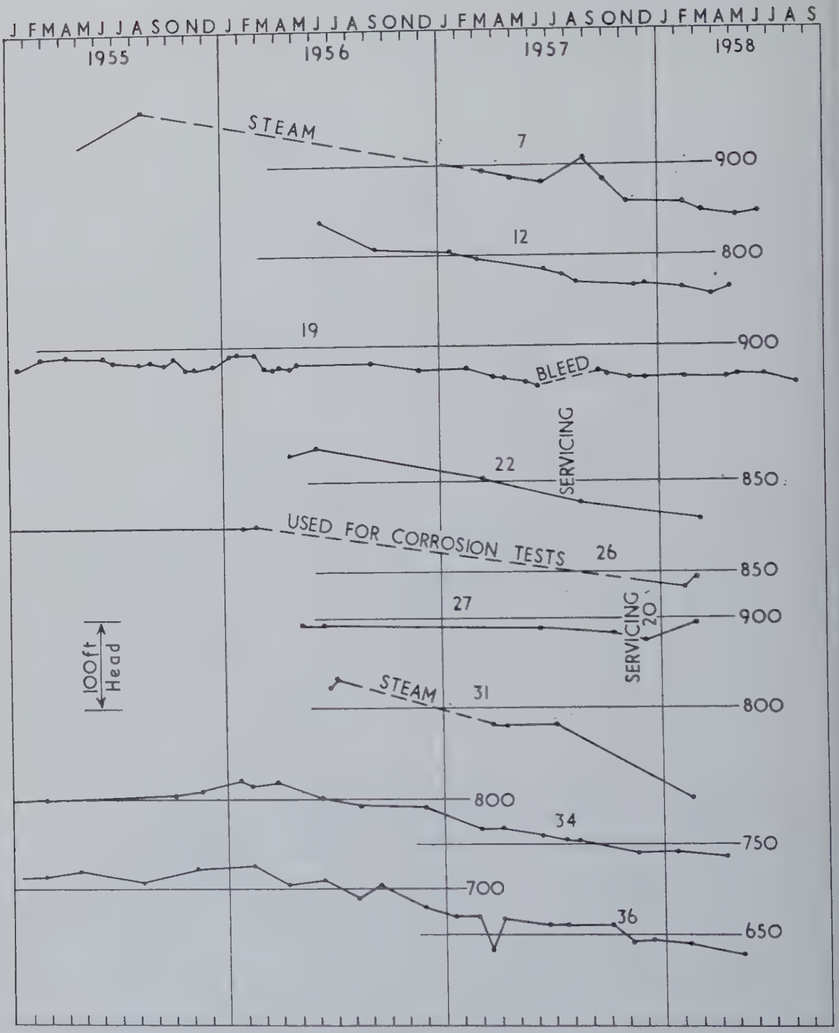

Fig. 8.—Variations in head at individual holes. Datum 500 ft above sea-level.

Boiling

In places where ground-water temperatures are close to the boiling-point, a decline in pressure without a corresponding decline in temperature will, of course, lead to boiling. Herein lies the explanation for the sudden displacement of the upper part of the water column by steam, in certain holes, accompanied by a rapid rise in wellhead pressure.

High steam pressure in the shut-in hole is, in fact, far from being the favourable omen that it was formerly considered to be, for it may presage the complete disappearance of thermo-artesian pressure, as, for instance, was seen in hole 7. Boiling removes latent heat, so that temperatures gradually fall to the saturation values corresponding to the new pressures, but this change is too small to be observed with certainty (a loss of 60 ft of head would lower the saturation temperature by only 3° at 230° C). The latent heat is carried upwards by the steam and the whole upper column is gradually brought to boiling.

Boiling takes place in the aquifer as well as in the drillholes; the steam travels up and accumulates under pressure beneath the mudstone. The increase in enthalpy observed at holes, such as 8A, that draw from the top of the aquifer, is probably due to this process. There is thus a paradoxical situation, in which falling temperature and pressure at lower levels can cause rising temperature and pressure at the top of the aquifer. This is an added reason for the failure to observe the withdrawal of stored heat; it also helps to explain the rather small decrease in natural heat escape which has accompanied exploitation, and the more marked decrease in chloride content of some of the hot-spring waters, chloride being insoluble in steam.

In a hydrothermal system where the confining beds happen to be very close to the surface, such an accumulation of steam may cause a temporary increase in surface activity, owing to the pressure under which it is held. This may occur even under natural conditions, if, for example, low rainfall or blockage of the recharge should reduce the pressure in the aquifer. The profusion of small explosion craters in some hydrothermal areas is perhaps due to such a cause. At Wairakei, on the other hand, some 500 ft of rocks and colder water overlie the steam, so that this type of surface activity would not appear unless the steam were presented with an easy passage through the mudstone.

THE HEAT SUPPLY

It has generally been assumed that hot water is fed into the Waiora aquifer from below, and a number of holes have been drilled to intersect faults in the ignimbrite and just above it, on the supposition that these might carry the feed. But none of these holes encountered the high enthalpy or pressure that was expected in such a feed.

Figure 7 shows several zones in which the decline in head has been small. Of these, the most interesting is that on the Waiora Fault at holes 20 and 27, for this is now an isolated high-head zone completely surrounded by lower values. Since this is in an area of intense exploitation, it must be a zone in which hot water is fed into the aquifer from below. In the undisturbed state, this hot water was forced to travel considerable distances through the pumice breccias to the passages in the overlying mudstone through which it could escape to the surface. Under these conditions, hot water would accumulate in the aquifer, pressure would build up, steep pressure gradients and rapid flow would disappear except in the mudstone. The location of the feed would then be effectively masked, as it is in Fig. 5, until exploitation was well under way.

This same masking process is responsible for the uniform chemical content of the water in the aquifer, and for the good correlation between temperature and hydrothermal alteration. The very completeness of the process is further proof of a long-established state of equilibrium in the Wairakei hydrothermal system. It is noteworthy that, in spite of this, Steiner (1955) affirmed the proximity of a feed channel to hole 20, after examining hydrothermal alteration in drill core samples.

Similar arguments may be applicable to the other high-head zones, but these are less well defined, both hydrologically and in extent. Hole 19 is at present an unproductive hole in an untapped sector of the field (cased into the ignimbrite, it is used for monitoring temperatures). The high head may be due simply to the absence of drawdown.

Along the Waiora Fault also, south-west of hole 30, the pattern is not yet fully developed, for this sector has only recently been tapped, except in hole 28, where free steam and gas make pressure figures unreliable. This south-west extension of the field and its possible connection with the surface heat flow around Karapiti Fumarole form the most attractive area for future exploration.

At the eastern end of the field, there is evidence of a low-head salient flanked by high-head holes, but it is difficult to obtain reliable, contemporaneous figures. Some of the holes have not been available for measurements, being in use for power generation, while others stand full of steam, with no measureable water level.

The possibility of a feed point in this sector is of great importance, for this is the downstream end of the aquifer, and if the output comes from storage alone, or from percolation of hot water from the west, the holes will be particularly subject to drawdown and exhaustion effects, as the abundance of steam in the shut-in holes might already indicate. Mr A. Steiner (pers. comm.) has examined fragments of rock ejected from holes in this sector, which, by their very intense alteration, support the contention that there is such a feed point. But the lack of correlation with core samples and the incompleteness of the hydrological data do not permit its location to be deduced.

Increased Heat Supply

In a previous paper (Studt, 1957), the author has given reasons for believing that an increase in the heat supply to the aquifer can be induced by exploitation, since the drillholes bypass the impedance of a part of the natural hot-water path through the rocks. It was suggested that most of this impedance is met near surface, and recent work throws further light on this.

Tests have shown no interaction between holes 20 and 27, although they are only 60 ft apart (Smith, 1958). Interaction is difficult to prove or disprove at Wairakei, for an extended stabilization time often follows wellhead adjustments, and any steam present in the rocks will tend to damp out rapid pressure disturbances, but it has been detected in holes spaced farther apart than these. Absence of interaction may imply a low impedance in the path through which the holes are fed. Of more importance is Smith's statement that aspiration tests have shown the pressure at the bottom of hole 27 to be practically unchanged for all output rates from zero to maximum. This implies that, during the tests, virtually all the impedance was in the drillhole and none in the rocks. Output at the time was rather lower than previous figures for this hole, and there is reason to believe that some throttling was taking place, for a calcite deposit was later removed from the liner casing close to the location of a sharp pressure drop which appeared in the test curves (Mr J. H. Smith, pers. comm.).

Nevertheless, the above facts suggest that this particular feed is quite capable of supplying more than the two holes 20 and 27. Despite this, the high-head zone is very limited in extent, so that there must be a high impedance to flow from the feed point to neighbouring holes. Although there may be some increase in the feed to the aquifer at this point as a result of general drawdown, the increase will be very much greater if the drillholes bypass this high impedance and actually tap the feed channel. Holes 20 and 27 do this; both passed through a fissure a short distance above the ignimbrite, in which there was evidence of rapid flow. The nearby holes 25, 48, 51, and 55 do not, and the high impedance which baulks them may be a result of the intense silification which Steiner (1955) reported adjacent to the fissure.

If it is possible to drill additional holes to tap the fissure close to 20 and 27, until interaction between holes is observed, or until bottom-hole pressure varies with the output of the group, then a worth-while increase in heat supply may be achieved. Crowding of holes at a feed point is, of course, standard practice in water supply drilling, but it is complicated at Wairakei by the elaborate wellhead installations, so that space is at a premium. Wide-diameter holes, or deflected holes, may be possible solutions to this problem.

Maximum theoretical efficiency would be obtained when the operating bottom-hole pressure is the mean of aquifer and wellhead pressures. However, too great a reduction of pressure in the holes might cause flashing of the hot water to commence in the fissure, instead of in the hole as at present. The fissure itself might then become subject to calcite blockage which could not be cleared. The final solution would be a compromise between these two considerations.

Whether an increase might be expected in the heat supply to the eastern sector of the field is uncertain. The Waiora Formation is thicker here, and no massive rocks are known close to the drillholes. In permeable beds, a localized feed could exist only if its path were surrounded by a curtain of silicification, or some other effective barrier to dispersion of the incoming fluids in the ground water. None has been located so far.

If increased heat supply to the Waiora aquifer can be obtained, it may come either from storage at some lower level, in which case its life would be limited like that of the stored heat above, or through increased flow from the ultimate source at depth, in which case it may, for practical purposes, be considered permanent. Either would be a valuable addition to the high-pressure resources of the Wairakei field.

THE INFLUENCE OF FAULTING

An interesting feature is the juxtaposition of highs and lows in the piezometric surfaces, especially along the Waiora Fault. Just as a high-head zone may mark a hot-water feed into the aquifer, so a low-head zone may mark a place where it escapes into the overlying beds through the fractured mudstone. The zone to the north-east of hole 31 is probably associated with the escape of the water feeding the hot springs of Geyser Valley.

However, it is also possible that such a fault initially carries hot water throughout its length solely owing to the pressure build-up in the aquifer. Under intense exploitation, it may carry this water only in certain sections, the adjacent sections being taken over by colder water flowing in from the surrounding country. Thus holes 24 and 29 are among the very few which have shown a fall in temperature; their early history gave promise of good output, but they deteriorated rapidly. Hole 24 was subsequently deepened, penetrating 700 ft of shattered, hydrothermally altered ignimbrite, but has not achieved more than 75% of its initial productivity.

This possibility of rapid penetration of cold water along permeable paths into the production area is important, because it may lead to deterioration in output of some of the holes before much of the stored heat can be utilized. The situation is akin to that of oilfield management, where an attempt is made to secure an even advance of the water behind the oil, with no salients which might cut out wells while much of the oil remains untapped. But it is complicated by the fact that the very fault which must be drawn on to increase the heat supply may bring in cold water, as well as hot,

ACKNOWLEDGEMENTS

The arguments in this paper have been based almost entirely on the long series of temperature, pressure, and water level measurements made in the Wairakei drillholes by the Geothermal Measurements Staff of the Ministry of Works. The author is indebted to the Engineer-in-Chief, and to the Project-Engineer, Wairakei, for making this material available for study and for co-operation in making additional measurements where these were required. Thanks are also due to Mr T. Grant Taylor, of the New Zealand Geological Survey, for enlightening discussion of hydrological problems, and to Mr A. Steiner, also of the New Zealand Geological Survey, for much petrological information.

REFERENCES

Banwell, C. J., 1955: Physical Investigations. *In* Geothermal Steam for Power in New Zealand. *N.Z. Dep. sci. industr. Res. Bull. 117*: pp. 45–74.

———, 1957: The New Zealand Thermal Area and its Development for Power Production. *Amer. Soc. mech. Engrs Trans. 79, 2*: 255.

Grange, L. I. (Compiler), 1955: Geothermal Steam for Power in New Zealand. *N.Z. Dep. sci. industr. Res. Bull. 117.*

Gregg, D. R., 1958: Natural Heat Flow from the Thermal Areas of Taupo Sheet District (N 94). *N.Z. J. Geol. Geophys. 1*: 65–75.

Grindley, G. W., 1957: Geothermal Power. *In* "Science in New Zealand". Reed, Wellington; pp. 112–22.

Smith, J. H., 1958: Production and Utilization of Geothermal Steam. *N.Z. Engng 13 (10)*: 354.

Steiner, A., 1955: Hydrothermal Rock Alteration. *In* Geothermal Steam for Power in New Zealand. *N.Z. Dep. sci. industr. Res. Bull. 117*, pp. 21–26.

Studt, F. E., 1957: Wairakei Hydrothermal System and the Influence of Ground Water. *N.Z. J. Sci. Tech. B 38*: 592–622.

White, D. E., 1957: Thermal Waters of Volcanic Origin. *Geol. Soc. Amer. Bull. 68*: 1637–58.

Wilson, S. H., 1955: Chemical Investigations. *In* Geothermal Steam for Power in New Zealand. *N.Z. Dep. sci. industr. Res. Bull* 117, pp. 27–42.

Wooding, R. A., 1957: Steady State Free Thermal Convection of Liquid in a Saturated Permeable Medium. *J. Fluid Mechanics 2, 3*: 273–85.

APPENDIX

PRESSURE COMPUTATIONS

Temperatures are measured at 100 ft intervals in the shut-in drillhole and each successive value is taken to represent conditions in the 50 ft above and below the point of observation. The densities corresponding to these successive temperatures are then simply added, from the observed water level down to the selected datum, together with the head equivalent to the recorded wellhead pressure. The total gives the head, in hundreds of feet of cold water at the datum.

Temperature measurement is accurate to ±2° C. and in a 2,000 ft hole the error due to inaccurate sampling and measurement is likely to be less than ±4 ft of head. Since this error is small compared with others involved, it is permissible, where a hole does not extend to the desired depth, to extrapolate several hundred feet below the bottom using temperatures taken from nearby holes.

Wellhead pressure measurement is accurate to better than 5 lb per sq.in., say, ±10 ft of head. Pressure may drift during the temperature run; if the drift is small, a mean value is used, but if it is large, the data are rejected entirely.

The most serious error is in the measurement of water level. Positive errors predominate, because steam and gas bubbles tend to lower the density of the column and raise the water level; there are occasions, for instance, when water is found at the wellhead although such a water

TABLE 1.—Pressure Computations.

HOLE 19: Run, 1525; date, 19 June 1958; elevation, 1,296 ft; W/L, 1,296 ft; wellhead pressure, 74 psig.

Elevation (ft)	Temperature (° C)	Density (g/cc)	Head (100ft)	Elevation (ft)
			1·71	WHP
1,296	54	0·99	2·20	1,246
1,196	127	0·94	3·14	1,146
1,096	182	0·89	4·03	1,046
996	192	0·87	4·90	946
896	199	0·86	5·76	846
796	206	0·86	6·62	746
696	213	0·85	7·47	646
596	217	0·84	8·31	546
			8·69	500
496	221	0·84	9·15	446
396	226	0·83	9·98	346
296	229	0·83	10·81	246
196	232	0·82	11·63	146
96	237	0·81	12·44	46
-4	241	0·81	13·25	-54
-104	244	0·80	14·05	-154
-204	247	0·80	14·85	-254
-304	247	0·80	15·65	-354
-404	247	0·80	16·45	-454
			16·82	-500
-504	247	0·80		

Head at +500 datum = 870 ft.
-500 datum = 1,680 ft.

HOLE: 29: Run, 1383; date, 13 January 1958; elevation, 1,373 ft; W/L, 1,373 ft; wellhead pressure, 15 psig.

Elevation (ft)	Temperature (° C)	Density (g/cc)	Head (100ft)	Elevation (ft)
			0·35	WHP
1,373	30	1·00	0·85	1,323
1,273	102	0·96	1·81	1,223
1,173	125	0·94	2·75	1,123
1,073	150	0·92	3·67	1,023
973	172	0·90	4·57	923
873	187	0·88	5·45	823
773	198	0·87	6·32	723
673	202	0·86	7·18	623
573	202	0·86	8·04	523
			8·24	500
473	210	0·85	8·89	423
373	213	0·85	9·74	323
273	220	0·84	10·58	223
173	230	0·82	11·40	123
73	236	0·81	12·21	23
-27	240	0·81	13·02	-77
-127	242	0·81	13·83	-177
-227	245	0·80	14·63	-277
-327	246	0·80	15·43	-377
-427	248	0·80	16·23	-477
			16·43	-500
-527	247	0·80		

Head at +500 datum = 820 ft.
-500 datum = 1,640 ft.

HOLE 34: Run, 1318; date, 18 November 1957; elevation, 1,312 ft; W/L, 1,262 ft.; wellhead pressure, nil.

Elevation (ft)	Temperature (° C)	Density (g/cc)	Head (100ft)	Elevation (ft)
1,312				
1,212	22	1·00	1·00	1,162
1,112	46	0·99	1·99	1,062
1,012	57	0·99	2·98	962
912	73	0·98	3·96	862
812	89	0·97	4·93	762
712	104	0·96	5·89	662
612	114	0·95	6·84	562
			7·42	500
512	124	0·94	7·78	462
412	134	0·93	8·71	362
312	144	0·92	9·63	262
212	152	0·91	10·54	162
112	159	0·91	11·45	62
12	164	0·90	12·35	-38
-88	170	0·90	13·25	-138
-188	176	0·89	14·14	-238
-288	181	0·89	15·03	-338
-388	185	0·88	15·81	-438
-488	187	0·88		
			16·36	-500

Head at +500 datum = 740 ft.
-500 datum = 1.640 ft.

level proves quite inconsistent with other data. Latterly, it has been the practice to bleed off steam and gas from the wellhead before making the run down the hole; this improves the accuracy of the water-level measurement, and reduces drift in wellhead pressure, at the cost of a small but systematic error in temperatures. This error gives a negative bias, offsetting the positive bias mentioned above.

However, there remain holes in which active boiling is believed to be taking place, making it impossible either to bleed effectively or even, in some cases, to measure a water level at all. Such holes yield little quantitative information.

Some typical examples of pressure computations are set out in Table 1.

Breaks in the casing of the holes, caused by corrosion combined with thermal stress, are not uncommon. Often the presence of a break is not apparent until it is searched for, and the effect upon the computed head must be considered. A casing break in the aquifer itself will not materially affect the results if the assumptions already made are valid, particularly the assumption that there is no rapid vertical flow through the rocks. A break within the confining beds will not affect the results unless it communicates with a low-impedance path through these beds. Breaks are important only if they occur in or communicate with the permeable breccias of the Wairakei Formation, allowing hot water under high thermo-artesian head to escape into these beds from the aquifer below. When this happens, the computed head is abnormally low; as has been observed in hole 23.

CORRIGENDA

N.Z. J. Geol. Geophys. 1.

The Geology of the Atiamuri Dam Site *by B. N. Thompson*

P. 300; line 8. *For* Atiamuri Pumice Breccia
read Whangapoa Beds.

Bougner Anomaly Map of New Zealand *by E. I. Robertson and W. I. Reilly*

Fig. 1—facing p. 562.

The value on the contour enclosing the town of Whakatane (North Island) is — 20 mgal, and of the adjacent contour, 0 mgal.

Measurement of Compression and Tension: Some Applications *by G. J. Lensen*

P. 567, Fig. 2.

The values — 10 — 20 — 30 in the north-west of the South Island should read + 10 + 20 + 30

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